OPTIMAL DESIGN OF BOILER CONTROL LOOPS

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ABSTRACT

One of the main steps in the design of steam generators control systems is the modelling of steam generators. In this work, a boiler model is used to design and verify more accurate controllers. The superheat steam pressure controller and the drum water level controller are tested for that model. Then, an optimization technique of Zettle is used to optimize the controllers. The problems appeared from the traditional feedwater controller are solved using three elements feedwater controller. The problems of superheater leakage or feedwater loss through the continuous blow down using three elements feedwater controller are considered and tested for the suggested model. Then the optimized performance is compared with the real performance of Damanhour thermal power plant which gives good results.

Keywords

Boiler models, Boiler control, Optimal control, Computer aided control systems design.

1. INTRODUCTION

The problem of boiler control are widely discussed in the literature.

Arne [1] introduced the multivariable control system of the boiler which is based on concepts of modern control theory and extensive use of interactive computer programs and real time simulation. The control system is designed to maintain the drum level, drum pressure and steam temperature at prescribed reference values given by the load conditions. The boiler studied in his work has a normal steam production of 29.2 kg/s.

Ali Feliachi [2] presents a different approach via optimal control theory to the design of water level controller for steam generators in large pressurized water reactors.

A steam generator water level controller consists of a three elements feedwater controller is discussed. The three elements are feedwater flow, steam flow and water level error. The level error is sent through a PI controller to eliminate steady state level errors. The output from the PI controller is added to the difference between the feedwater flow rate and steam flow rate, and the resultant signal is sent to a PI controller to eliminate steady state errors in feedwater flow and set the main feedwater valve position signal.

In a previous work [3] a steam generator mathematical model as mass, volume and energy balance was proposed. That model was tested using real data collected from Damanhour thermal power plant and used to investigate the dynamic behaviour of that plant.

In the present work, that model is used to verify and design more accurate controllers. To attain a better performance of the boiler, an optimization technique is used to optimize the controller constants (proportional and integral constants) for the pressure and level controllers to minimize the error between pressure and drum level set points and their actual values. The control loop is shown in Figure (1).

2. MATHEMATICAL MODEL

Referring to De-Mello [4] Awad [3], the relations applied to a drum type boiler and that defining the process dynamics for the model are based on the following assumptions.

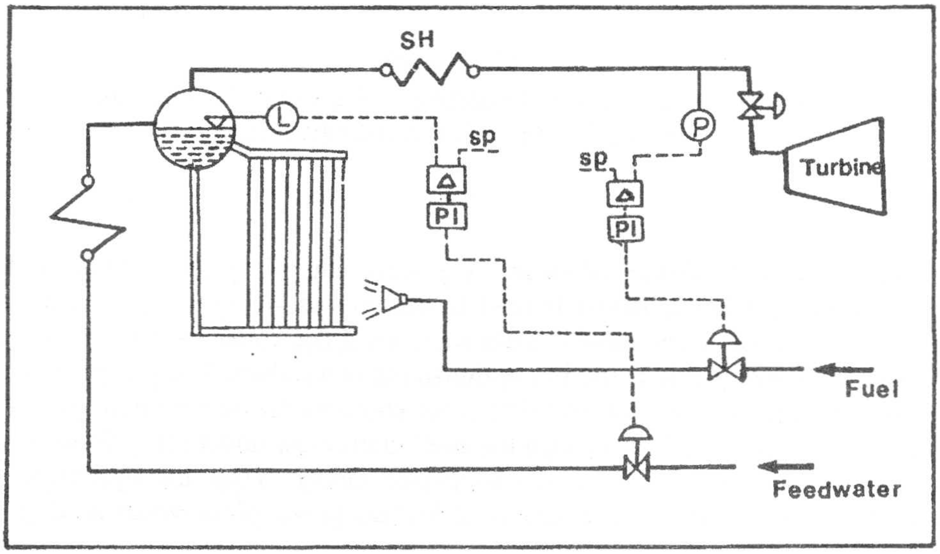


Figure 1. Superheated steam pressure control with drum level control.

1. Feedwater has enthalpy (h_{fw}) and a flow rate ($\dot{m}_w$) mixes with saturated water from drum and the mixture flows down the downcomer at a circulation flow rate ($\dot{m}_r$).
2. Heat absorbed by fluid in waterwalls is uniformly distributed.
3. Velocities of steam and water are assumed equal.

2.1 Mass Balance

$$\frac{d}{dt}\left(M_f + M_g + M_{sc} \right) = \dot{m}_w - \dot{m}_s \tag{1}$$

2.2 Volume Balance

$$(M_f + M_{sc}) \, . \, v_f + M_g \, . \, v_g = V \tag{2}$$

2.3 Energy Balance

$$\frac{d}{dt}\left(M_f.h_f + M_{sc}.\left(\frac{h_f + \bar{h}_r}{2}\right) + M_g.h_g - K.V.P_o\right) = \dot{Q}_w + \dot{m}_r.\bar{h}_r - (\dot{m}_r - \dot{m}_w).h_f - \dot{m}_s.h_g \tag{3}$$

where:

v_f, v_g, h_f, h_g are steam and water properties and can be calculated as functions of drum pressure.

2.4 Calculation of Pressure in Superheater Sections

The superheated steam pressure in superheater sections can be expressed as in the following equations:

$$P_o = P_1 + (\dot{m}_g)^2 K_1 \tag{4}$$

$$P_1 = P_2 + (\dot{m}_{12})^2 K_2 \tag{5}$$

$$P_2 = P_3 + (\dot{m}_{23})^2 K_3 \tag{6}$$

$$\dot{m}_t = K_v . \, P_3 \tag{7}$$

2.5 Calculation of Superheater Sections Flow Rates

Flow rates between superheater sections are calculated from the continuity equations:

$$\dot{m}_{23} = \dot{m}_t + V_3 \frac{\partial \rho_3}{\partial P_3} \times \frac{dP_3}{dt} \tag{8}$$

$$\dot{m}_{12} = \dot{m}_{23} + V_2 \frac{\partial \rho_2}{\partial P_2} \times \frac{dP_2}{dt} \tag{9}$$

$$\dot m_5 = \dot m_{12} + V_1 \frac{\partial \rho_1}{\partial P_1} \times \frac{dP_1}{dt} \tag{10}$$

2.6 Calculation of Drum Level

Volume occupied by the steam mixture

$$= (V - V_o) - M_{sc} \cdot v_f \tag{11}$$

The portion of this volume occupied by liquid

$$= 1 - \frac{\dot m_{ws} \cdot v_g}{2(\dot m_r - \dot m_{ws})(v_f + \dot m_{ws} \cdot v_g)} \tag{12}$$

Mass of fluid in drum

$$M_{fd} = M_f - M_{fww} \tag{13}$$

Change in drum level

$$D_1 = \frac{(M_{fd} - M_{fdo}) \cdot v_f}{D_A} \tag{14}$$

The control loops considered are shown in Figure (1). The superheat steam pressure is controlled from the fuel and air flows, the drum level is controlled by the feedwater as one element control.

3. CONTROLLER OPTIMIZATION

The optimization technique given in [5 & 6] are used to optimize the controller constants. The design procedure adopted here uses a time domain optimization technique to find optimal values of feedwater controller proportional and integral constants, and superheat steam pressure controller proportional and integral constants. It is assumed that the superheat pressure is to be stabilized at its initial value. So the pressure error is calculated as the difference between the initial superheat pressure and the instantaneous superheat pressure. The drum level is required to be stabilized at the zero level. The drum level error is assumed to be positive if the drum level is higher than the zero level and negative if the drum level is lower than the zero level.

The optimized parameters are selected to minimize the following objective functions:

$$1 - \int_0^t [k_o \cdot |\text{pressure error}| + |\text{level error}|.]\,dt \tag{15}$$

$$2 - \int_0^t [k_o \cdot (\text{pressure error})^2 + (\text{level error})^2.]dt \tag{16}$$

$$3 - \int_0^t \text{time}.[k_o \cdot |\text{pressure error}| + |\text{level error}|]\,dt \tag{17}$$

$$4 - \text{settling time} \int_0^t [k_o \cdot |\text{pressure error}| + |\text{level error}|.]\,dt \tag{18}$$

where k_o is a magnifying factor to give the pressure error the same weight as drum level error.

4. THREE ELEMENTS DRUM LEVEL CONTROL

It is evident that the level will remain constant until the feedwater flow rate is equal to the steam flow rate with the possible drains included. Should this condition of balance suddenly fail the level would start increasing or decreasing at a proportional speed to the difference in the flow rates. This statement however would be valid if a homogeneous liquid was in the drum. Actually the water steam mixture has a mean specific weight that may remarkably change according to the pressure. By increasing the steam demand a lowering in the boiler pressure occurs and the steam bubbles present in the water mass expand all at once (evaporation and increase of steam bubbles) causing a real swelling of the water mass and the level in the first transient period increases instead of decreasing.

For these reasons, the most reliable control system is the three elements drum level control. The three elements are: drum level, feedwater flow rate and the steam flow rate.

5. RESULTS AND DISCUSSION

For Damanhour power station, the boiler outputs due to a step change in the turbine valve position are recorded. With an initial guess for controller parameters the different objective functions are built. The parameters are changed due to the strategy in [5 & 6] to minimize the different objective functions. The performances of the boiler for the different obtained parameters are compared. Also single element and 3-element controller parameters are optimized and tested.

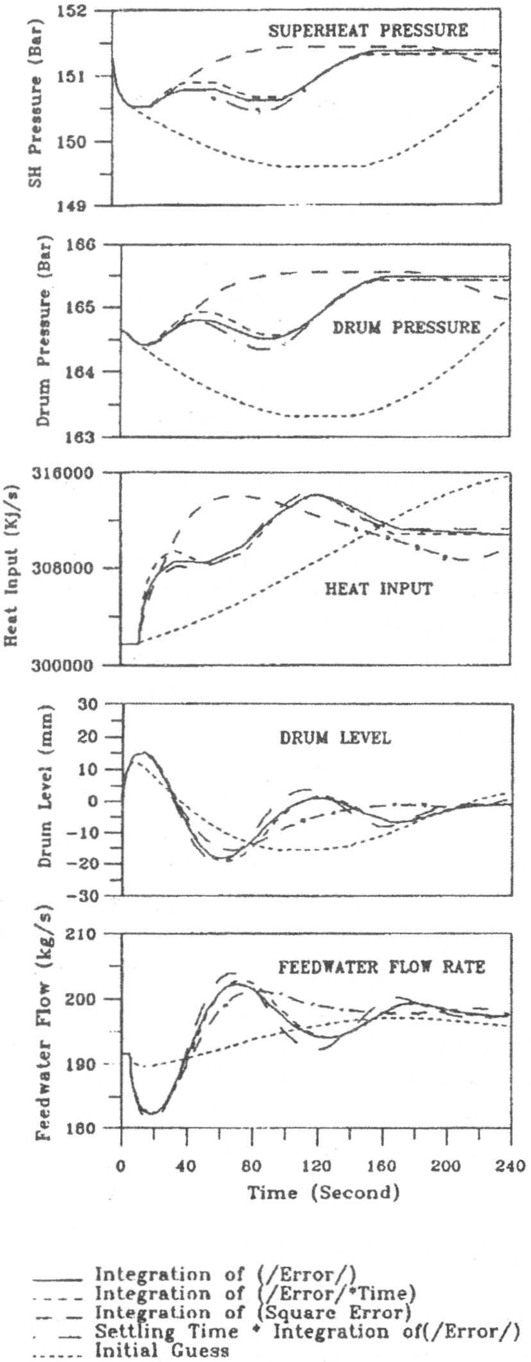


Figure 2. Comparison between different objective functions applied to the 1-element drum level control for damanhour power plant.

5.1 Comparison Between Controller Performance Before and After Optimization

Figure (2) shows the controllers performance before and after optimization. Input disturbance is a 3% step increasing in turbine valve position.

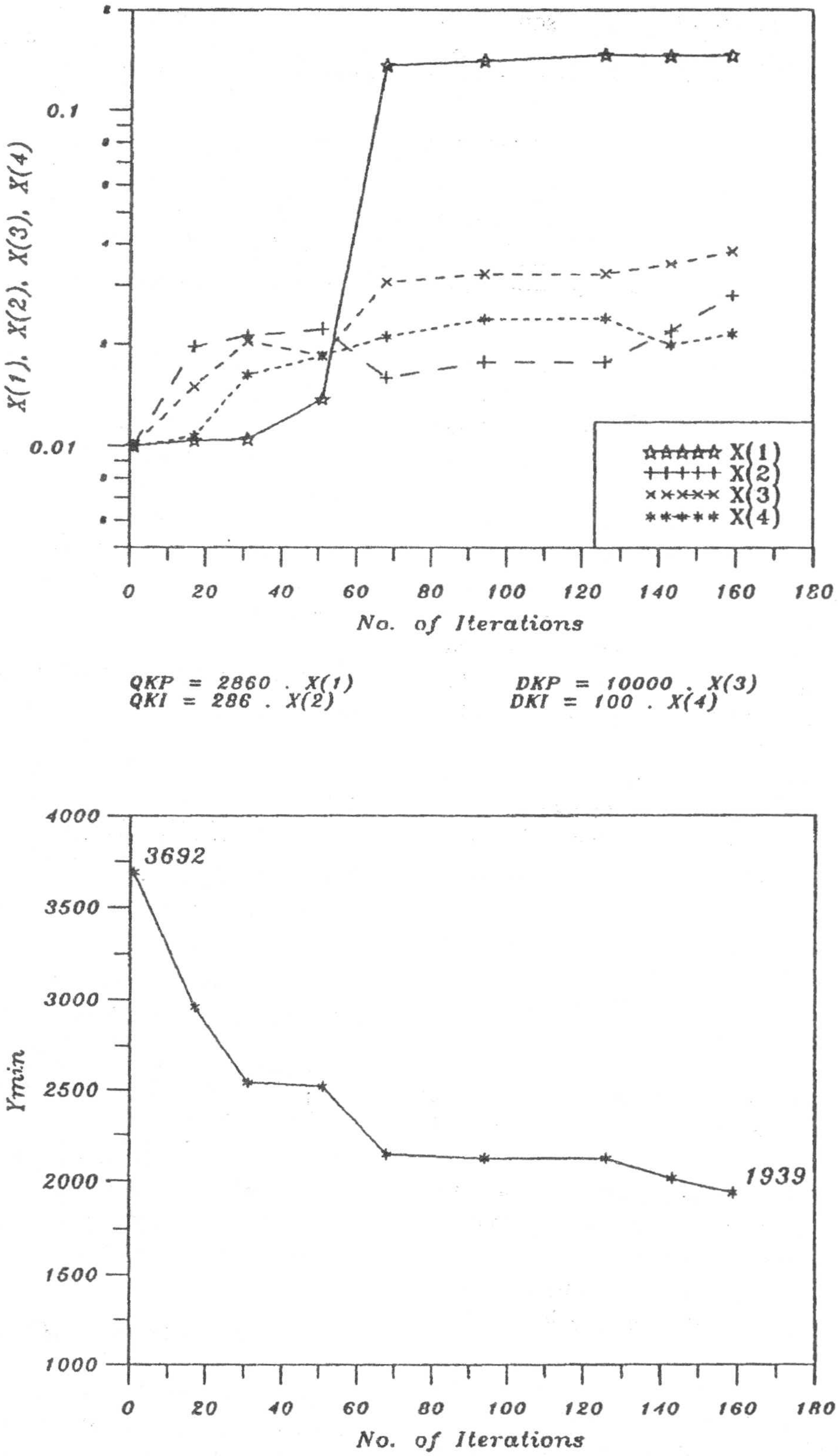
Studying these curves we find that:

1. Before optimization the controllers are not able to stabilize the process variables through 240 s. But after optimization the superheat steam pressure stabilized through 160 s where the drum level took 200s to reach its set point.
2. The swell and shrink phenomena arises from the change in drum pressure disturbes the drum level in the first transient period.
3. In the second transient period, the superheat steam pressure controller tries to keep the superheat pressure at its set point. So the controller increases the heat added which increases the rate of evaporation and the change in the rate of heat added affects on the drum level. As a result the drum level is not stabilized until the superheat pressure is stabilized.
4. In the second transient period from about 60 s and up to 200 s it is very clear that the drum level is directly proportional to the rate of heat added, the higher the rate of heat added the higher the drum level (from 80 s to 140 s). and the lower the rate of heat added, the lower the drum level (from 140 s to 200 s). We can explain this result from the equations defining the model. Increasing the heat added, the mass of saturated vapor (M_g) increases and (M_f) decreases. As the specific volume of saturated steam is higher than the specific volume of saturated water, so the drum level increases and the new value of drum level can be calculated according to M_f, M_g.

The optimization path using the objective function given in equation (15) is shown in Figure (3). In this test we started with all parameters equal 0.01 as initial guess. It is found that the value of objective function related to this initial guess is 3692 mm which decreased by optimization to 1939 mm with a percentage reduction equal 47.5 % after 160 iterations.

5.2 Comparison Between Different Objective Functions

Referring to Figure (2), the boiler performance obtained with the objective function given in relation (3) is very similar to that using equation (1), but it is found that the optimization path is different from that obtained by equation (1). Although the optimal parameters are nearly the same. Using equation (3) took a longer computer running time and reached the optimum parameters after about 320 iterations. The percent reduction by this objective function is 64 %.



QKP = 2860 . X(1)
QKI = 286 . X(2)

DKP = 10000 . X(3)
DKI = 100 . X(4)

Figure 3. Optimization path for the superheated steam pressure control with drum level control for the objective function equal to the integration of the absolute error.

Table 1. Comparison between different objective functions for superheat steam pressure controller with 1-element drum level controller

Objective function	Optimum parameters				Value of objective function		% Reduction
	X(1)	X(2)	X(3)	X(4)	Before	After	
(1)	0.145	0.0278	0.03797	0.02150	3692	1939	47
(2)	0.095	0.082	0.038	0.0264	149926	17546	88
(3)	0.178	0.0276	0.0372	0.0214	416988	149985	64
(4)	0.138	0.0252	0.0407	0.0236	1147773	408999	64

The objective function with the absolute error square is given in equation (2) and the boiler performance is also shown in Figure (2). From these curves we notice that the drum level is more stabilized due to the low rate of change in heat added.

Referring to Table (1), the optimum pressure controller integral constant with the objective function given in equation (2) is higher than that with objective function given in equation (1). This higher constant means lower time required for the process variable to stabilize. So the superheat steam pressure stabilized more faster with equation (2). As a result, the drum level also stabilized faster.

Using the square objective function equation (2), the program running time is longer than using equation (1) and the number of iterations is about 400 with a percentage reduction in objective function equal to 88 %.

Using objective function including settling time (equation (4)), the optimum parameters are reached after 320 iterations and the percentage reduction in objective function equal 64.4 %.

5.3 Comparison Between 3-Elements Drum Level Controller and 1-Element Drum Level Controller

A comparison was done between the optimum three elements drum level controller and the optimum one element drum level controller Figure (4).

Table (2) shows the optimum constants for the 3-elements drum level controller with various objective functions.

Table (3) shows the value of objective function and its percent reduction against the 1-element controller with different objective functions. Figure (5) shows boiler performance using different objective functions.

Studying the controller performance shown in Figure (4) for the 1-Element and 3-Elements, we obtain that:

1. Using 1-Element drum level controller, the superheat steam pressure took 160 seconds to stabilize where the drum level took 210 seconds to reach its initial value.
2. Using 3-Element drum lever controller, the superheat pressure reached its initial value after 60 seconds and the drum level stabilized after 100 seconds.

Table 2. Optimal controller parameters for different objective function with 3- element drum level controller.

Objective function	X(1)	X(2)	X(3)	X(4)	X(5)	YMIN
(1)	0.1811	0.0790	0.0774	0.03023	0.090	1377
(2)	0.125	0.0092	0.0756	0.0036	0.098	7544
(3)	0.100	0.0384	0.0538	0.0567	0.099	108929

Table 3. Comparison between optimum 1-element and 3-elements drum level controller with different objective function.

Objective function	1-Element	3-Element	Percent reduction
(1)	1939	1377	29%
(2)	17546	7544	57%
(3)	149985	108929	27%

5.4 Problems of 3-Elements Drum Level Control

Using 3-elements drum level control, a problem may appear due to the leakage in superheater when the boiler become older, or feedwater loss through continuous blowdown. This can interrupt the controller.

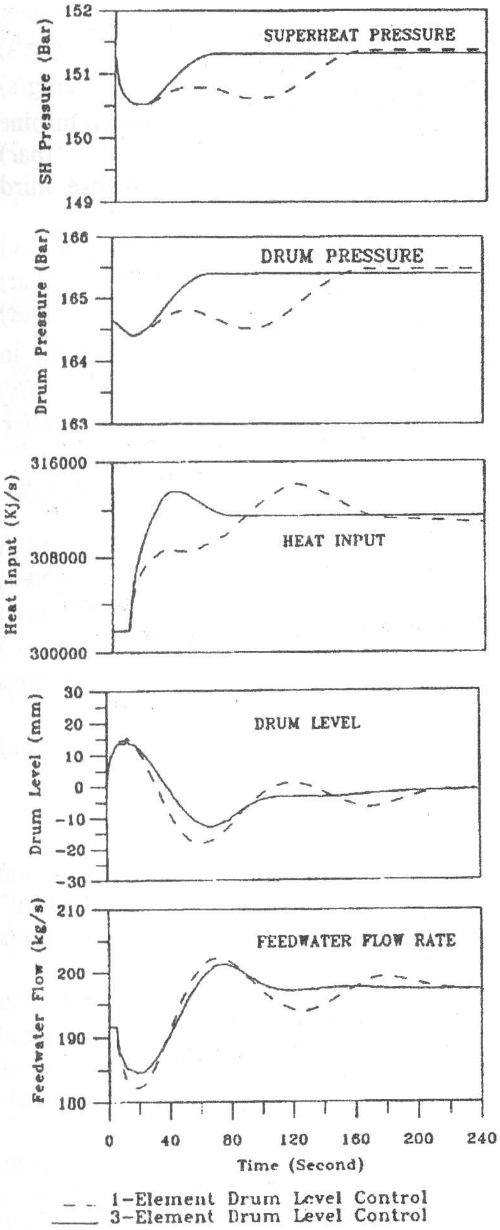


Figure 4. Comparison between the 3-elements and the 1-element feedwater controller applied for Damanhour power station.

A test was made in the optimized model assuming 2% and 5% superheat steam loss using the same controller constants calculated from optimization.

Values of objective function for each percent loss are shown in Table (4) and are compared with one element drum level controller.

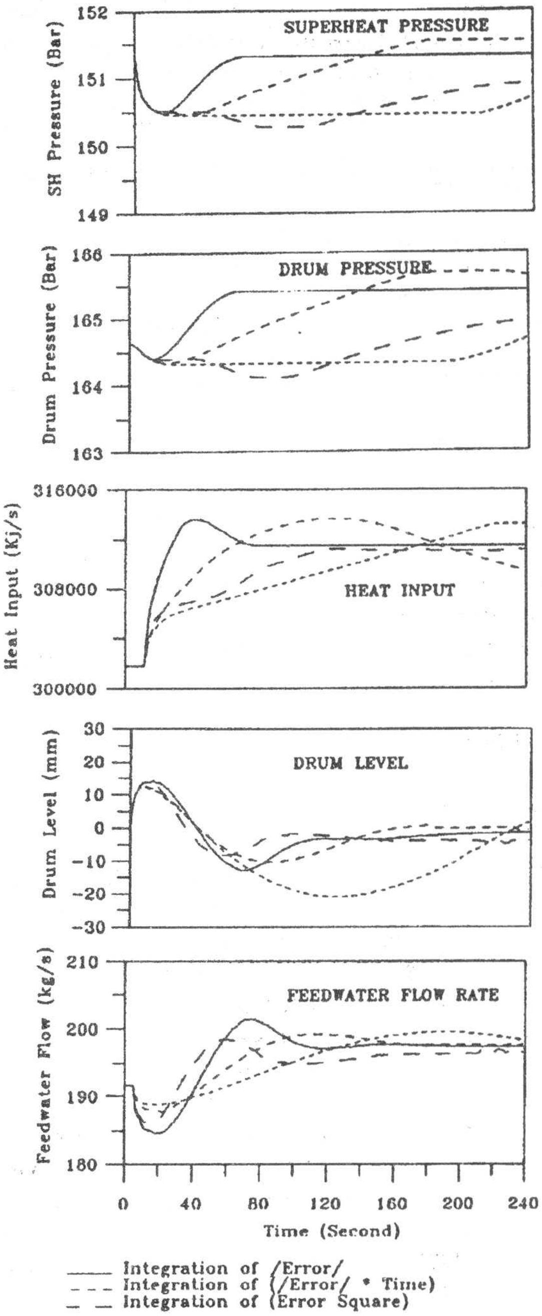


Figure 5. Comparison between different objective function for 3-elements drum level control applied damanhour power station.

It is shown that up to 5 % of superheat steam flow loss, the 3-Elements drum level controller is better than one element drum level controller.

Table 4 Comparison between optimum 3-element drum level controller with superheater leakage and 1-element drum level controller.

Case	Value of Ymin	% reduction of Ymin against 1-element
3-Elements drum level controller without leakage	1377	29%
3-Elements drum level controller with 2% leakage	1584	18%
3-Elements drum level controller with 5% leakage	1892	2.5%
1- Element drum level controller	1939	0%

6. CONCLUSION

It is concluded that using optimization, the controller constants can be calculated accurately to give the optimal performance. It is also shown that the 3-elements drum water level controller is better than the 1-element controller. And up to 5% superheat steam leakage, the 3-elements controller can be used.

NOMENCLATURE

D_A	Drum cross section area	(m^2)
D_1	Drum level	(mm)
DKP	proportional constant of drum level controller	
DKI	Integral constant of drum level controller	
h_r	Enthalpy of water entering waterwalls	(kj/kg)
h_f	Enthalpy of saturated water	(kj/kg)
h_g	Enthalpy of saturated steam	(kj/kg)
h_{fw}	Enthalpy of feedwater	(kj/kg)
K	Conversion constant	
K_v	Turbine valve constant	
K_1,	K_2, K_3 Coefficients relating pressure drop to flow rates square	($bar.s^2/kg^2$)
M_f	Mass of saturated liquid in waterwalls and drum	(kg)
M_g	Mass of saturated vapor in waterwalls and drum	(kg)
M_{sc}	Mass of subcooled liquid in waterwalls and drum	(kg)
M_{fd}	Mass of liquid in drum	(kg)
M_{fww}	Mass of saturated liquid in waterwalls	(kg)
$\dot{m}_w$	Feedwater flow rate	(kg/s)
$\dot{m}_s$	Steam flow rate	(kg/s)
$\dot{m}_r$	Recirculation flow rate	(kg/s)
$\dot{m}_t$	Turbine steam flow rate	(kg/s)
$\dot{m}_{23}$	Steam flow rate between second Superheater and third superheater	(kg/s)
$\dot{m}_{12}$	Steam flow rate between first Superheater and second superheater	(kg/s)
$\dot{m}_{ws}$	Steam generation	(kg/s)
P_3	Superheated Steam pressure before turbine valve	(bar)
P_2	Superheated Steam pressure before third Superheater)	
P_1	Superheated Steam pressure before second Superheater	(bar)
P_o	Drum pressure	(bar)
$\dot{Q}_w$	Heat transferred from tubes to fluid in waterwalls	(kj/s)
QKP	Propotional constant of pressure controller	
QKI	Integral constant of pressure controller	
X(I)	I = 1.4 scaled parameters for QKP, QKI, DKP, DKI	
v_f	Specific volume of saturated water	(m^3/kg)
v_g	Specific volume of saturated steam	(m^3/kg)
V	Volume of waterwalls and drum	(m^3)
V_D	Volume of drum	(m^3)
V_1, V_2, V_3	Volume of jumped Superheater sections	(m^3)
Y_{min}	Value of objective function	(mm)

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