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Modeling and Control of Water Level in Boiler Drum for Nassiriyah Thermal Power Plant

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Abstract: The boiler drum process is a nonlinear, complex and multivariable process which includes significant time delay. Therefore, the control on the water level in the drum is not easy and ideal. The first objective of this paper is to model the drum water level referring to 210 MW power unit for Nassiriyah thermal power plant. The second objective is to study the water level controller operation with its performance investigation. Firstly, the drum water level process has been modelled based on first principles by two models: the proposed simplified linearized model and the complicated nonlinear model. Then, a comparison between the extracted practical plant data and the water level results simulated by the two models demonstrate the validity of both models with very good approximations. Secondly, Proportional Integral (PI) controller based on three element water level control strategy and used in this plant, has been described and simulated by MATLAB/Simulink. The controller parameters have been selected according to practical considerations. These considerations are minimizing as possible, a number of the close and open commands to the feedwater flow control valve to extend its lifetime with maintaining the drum water level on a set point. The controller has been tested to evaluate its performance for different values of proportional gain (K_p), integral gain (T_i), gain of steam flow signal (Gx_2), and gain of mass feedwater flow signal (Gx_3). Firstly, the results show that selection of K_p is difficult because of the tradeoff between fast dynamic response and steady state performance. Secondly, the results show selection of T_i affects only steady state performance. Finally, the results show that selection of Gx_2 and Gx_3 plays an important role in stability of the drum water level.

Keywords: Boiler Drum, Water Level, PI Control, Three Element Level Control Strategy, Thermal Power Plant.

1 Introduction

MUCH of the electricity used in Iraq is produced in steam power plants and combined cycle power plants. The boiler represents a vital and an important part in these plants.

A drum boiler is a large cylindrical vessel which is approximately half filled with water. It acts as a water storage tank for boiler tubes and as a separator for between water and steam in the evaporation system. Water is used to generate the steam and cooling of water tubes for protection from overheating. The water level in the boiler drum should be maintained in the permitted range very carefully. If the level falls too low, there is a risk of dry-out. If the level rises too high, saturated steam is not separated well from water droplets because drum steam surface area will be reduced. This causes thermal shock for high temperature superheater tubes [1].

The first objective of this paper is to model the drum water level referring to 210 MW power unit for Nassiriyah thermal power plant. The second objective is to study important concepts in the water level controller operation with its performance investigation.

In this plant, the boiler has two Flow Control Valves (FCVs) to control on feedwater flow supplied to the boiler. The first valve is small startup valve, which also

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is known as the bypass FCV. The other valve is large main valve. Thus, there are two controllers: startup water level controller which is used to control the startup FCV and main water level controller which is used to control the main FCV. The main water level controller is designed for maintaining the water level in the boiler drum on a set point within load ranged 30-100% of rated load (63-210 MW). While the startup water level controller is designed for maintaining the water level in the boiler drum on a set point when the boiler starts in the operation or the load is less than 30% of rated load (63 MW).

The startup water level controller is based on two element control strategy (water level and position indicator of the startup FCV) because during starting the boiler, both the feed water flow and the main live steam flow are below the measurable ranges, and therefore, the level controller based on the three element control strategy results instability. In this case, it is effective to use two element control strategy in which the water level is controlled by the startup controller. However, the two element drum level control strategy does not perform properly once the boiler is fully operative. For full running condition of the boiler, changes of the load demand must be taken into the account. In this case, three element drum level control strategy is most effective. Therefore, this paper focuses on study of the main controller based on three element drum level control strategy.

The control on the drum water level is not easy and ideal because the boiler is highly nonlinear and multivariable process in addition the gains and time constants vary significantly with the change of the operating point (steam load) and disturbances. Moreover, it is inherently unstable due to the integrating effect of drum level [1, 2].

In Iraq, frequency of the power system is not regulated well about 50 Hz, where it is usually varied between 48.5 to 51 Hz. The frequency variations affect significantly on feedwater flow supplied by pumps causing instability of the drum water level in the power plants. Consequently, the water level controller outputs a lot of the commands of the open and the close to the FCV. This leads wear and tear on the FCV and diminishing its lifetime [3]. In this paper, this problem will be considered and presented some suggestions to solve them.

Many papers are focused on modelling and control of a boiler drum. Barbara Molloy [1] developed first principles model of the boiler drum. She also developed predictive controllers (fuzzified linear predictive controller and nonlinear predictive controller). The results comparison demonstrated that two predictive controllers improve significantly boiler control performance than conventional PI boiler controller. K. Begum *et al*. [2] developed an intelligent model to control the water level in the boiler drum. The parameters of boiler drum level control system are determined using PID control tuning methods such as Ziegler-Nichols method, Tyreus-Luyben method and Internal Model Control (IMC). They showed that the use of IMC with feedforward controller improves the performance to a great extent than both of these Ziegler-Nichol and Tyreus-Luyben PID tuning techniques. W. Zhuo *et al*. [4] presented fuzzy controller and PID controller to control the boiler drum water level system. The results comparison between the two controllers showed that the fuzzy controller improves the static and dynamic characteristics of the drum level control system obviously compared to PID controller. The above works [1, 2, 4] showed that the intelligent level control methods such as IMC and fuzzy control are better performance than the PID control because the PID control used in these works is based on one element level control strategy. So, in this paper, the PI control based on three element level control strategy is presented with evaluation of its performance.

2 Thermal Power Plant Description

This paper uses extracted practical data from thermal power plant located in Nassiriyah city/Iraq. Water-steam cycle used in this plant is based on the familiar Rankine cycle as shown in Fig. 1. Generally, a thermal power plant converts the chemical energy of fuel into the electrical energy. This is achieved by raising the steam in the boiler, expanding it through the turbine and coupling the turbines to the generators which converts the mechanical energy into the electrical energy.

Firstly, fossil fuel with air is burnt in the furnace. The fire ball temperature reaches 1400 ^{o}C. Hot combustion gases transfer heat to feedwater passing through tubes (risers) in the boiler. The incoming water (feedwater) increases its temperature when passing through risers until it becomes saturated steam and saturated steam then is separated from water in the boiler drum by 48 internal cyclones. This operation is called the natural circulation of the boiler. The saturated steam from the boiler drum is taken to three superheater stages: the low temperature superheater, platen superheater and final superheater. The superheated steam temperature may rise above specific limit causing overheating to the tubes. Therefore, it is necessary to inject the superheater stages by water coming from feedwater pumps during starting the unit operation or water coming from boiler condensers after starting the unit operation. The superheated steam from the final superheater is taken to the High Pressure Cylinder (HPC). In the HPC, the steam pressure is used to rotate the turbine. The out coming steam from the HPC is taken to the reheater in the boiler to increase its temperature since the steam becomes wet at the HPC outlet. After the reheating, this steam is taken to the Intermediate Pressure Cylinder (IPC) and then to the Low Pressure Cylinder (LPC). The outlet of the LPC is sent to the condenser for condensing back to water by a cooling water system.

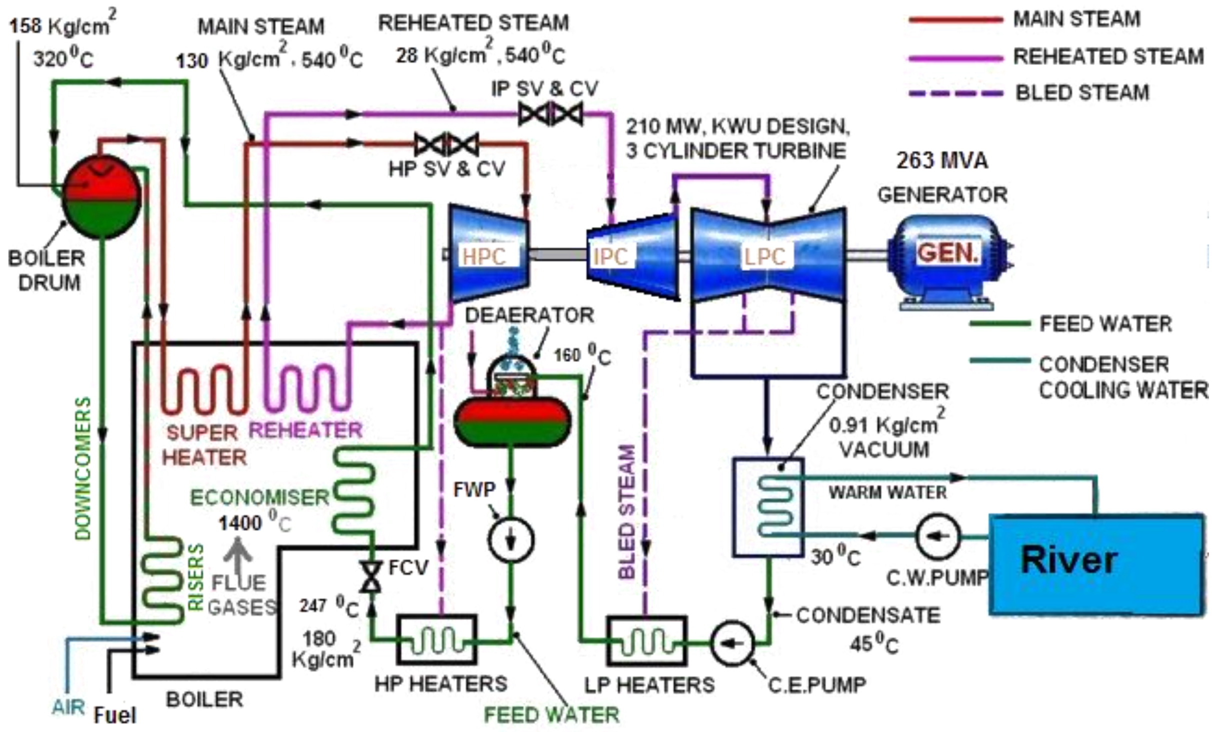

Fig. 1 Water-steam cycle diagram of Nassiriyah thermal power plant.

This condensed water is collected in the hotwell and is again sent to the boiler in a closed cycle. The rotational energy imparted to the turbine by HPC, IPC and LPC steam is converted to the electrical energy by the generator [5].

3 The Mathematic Modeling of the Boiler Drum System

The boiler drum system model is derived from first principles for the laws of physics. The boiler drum system can be represented by two models: proposed simplified linearized model and complicated nonlinear model. The proposed linearized model is simple and sufficient to represent the boiler drum, especially, in issues of stability analysis and parameters selection of the drum water level controller.

Firstly, the drum is a horizontal cylindrical vessel as shown in Fig. 2. The water volume (V_w) in the drum at water level (L) is calculated by [6]:

$$V_W = W\left[R^2\cos^{-1}\left(\frac{R-L}{R}\right)-(R-L)\sqrt{2RL-L^2}\right] \quad (1)$$

where R is radius of the cylinder and W is length of the cylinder. A result of the $\cos^{-1}$ function is radius. In fact, the drum contains 48 internal cyclones which are used to separate saturated steam from water droplets. These cyclones take a volume inside the drum. However, its volume is neglected in the volume calculation since it is very small volume with respect to the total drum volume. Derivation of water volume with respect to water level $\left(\frac{dV_w}{dL}\right)$ is given by:

$$\frac{dV_w}{dL} = 2W\sqrt{2RL-L^2} \quad (2)$$

In this plant, R is 800 mm and W is 24.3 m. The normal level is at the drum's midpoint (800 mm) and the admissible level is (800±50) mm. It is assumed that the drum level is controlled well and does not exceed the protection limits. Therefore, $\left(\frac{dV_w}{dL}\right)$ is approximately constant about the drum's midpoint (i.e. $L = R$) as shown in Fig. 3 and is given by:

$$\frac{dV_w}{dL} = 2WR = 38.88 \quad (3)$$

A boiler drum system behavior is captured by two laws of the global mass balance and the global energy balance. The inputs of the system are the heat flow rate to the risers (Q), feedwater mass flow (q_f) supplied to the drum and the steam mass flow (q_s). The system outputs are the drum pressure and the drum water volume (V_w). Thus, the system behavior is given by the below state space equations [7]:

$$e_{11}\frac{dV_w}{dt}+e_{12}\frac{dP}{dt} = q_f - q_s \quad (4)$$

$$e_{21}\frac{dV_w}{dt}+e_{22}\frac{dP}{dt} = Q + h_f q_f - h_s q_s \quad (5)$$

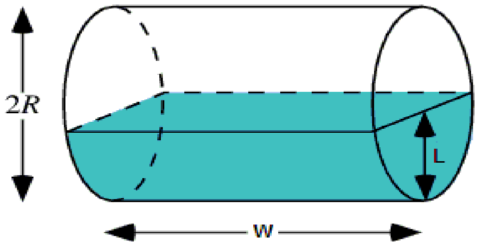

Fig. 2 Diagram of a horizontal drum.

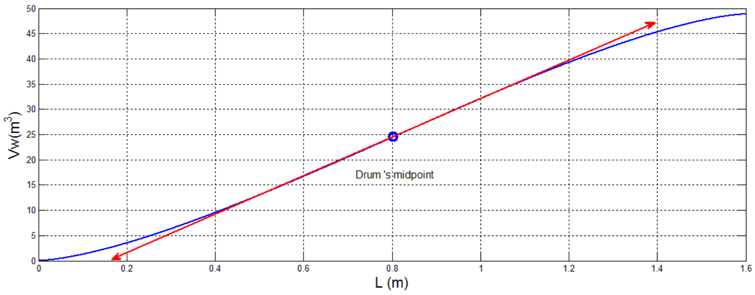

Fig. 3 Plot of the drum water volume with respect to the water level.

where

$e_{11} = \rho_w - \rho_s$,

$e_{12} = V_s \dfrac{\partial \rho_s}{\partial P} + V_w \dfrac{\partial \rho_w}{\partial P}$,

$e_{21} = \rho_w h_w - \rho_s h_s$,

$$e_{22} = V_s \left(h_s \frac{\partial \rho_s}{\partial P} + \rho_s \frac{\partial h_s}{\partial P} \right) + V_w \left(h_w \frac{\partial \rho_w}{\partial P} + \rho_w \frac{\partial h_w}{\partial P} \right) - V + m_t C_p \frac{\partial t_s}{\partial P},$$

V is the total boiler drum volume which is 48.858 m^3 for this plant,
V_w is the water volume in the drum,
V_s is the steam volume in the drum,
ρ_w is the specific density of the water,
ρ_s is the specific density of the steam,
h_f is the specific enthalpy of the feed water,
h_w is the specific enthalpy of the water drum,
h_s is the specific enthalpy of the steam drum,
m_t is the mass of the drum, downcomers and risers metal which is 278400 Kg and
C_p is the specific heat capacity of the used metal (carbon-steel) which is 490 J/Kg.

From (4) and (5), the system can be represented as matrices by the following equation:

$$\begin{bmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{bmatrix} \begin{bmatrix} \dfrac{dV_w}{dt} \\ \dfrac{dP}{dt} \end{bmatrix} = \begin{bmatrix} q_f - q_s \\ Q + h_f q_f - h_s q_s \end{bmatrix} \qquad (6)$$

Multiplying both sides by inverse of matrix $\begin{bmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{bmatrix}$, the system outputs are given by:

$$\begin{bmatrix} \dfrac{dV_w}{dt} \\ \dfrac{dP}{dt} \end{bmatrix} = \frac{1}{e_{11}e_{22} - e_{12}e_{21}} \begin{bmatrix} e_{22} & -e_{12} \\ -e_{21} & e_{11} \end{bmatrix} \begin{bmatrix} q_f - q_s \\ Q + h_f q_f - h_s q_s \end{bmatrix} \qquad (7)$$

The nonlinear boiler drum model based on (7) is simulated by MATLAB/Simulink as shown in Fig. 4. This model considers on the boiler drum dynamics clearly. The relationship between the water level as output and the water volume in the drum is represented by a lookup table block due to no inverse function in (1). For purpose of reading the drum water level easily by a unit operator, the level is measured from the drum's midpoint (800mm) since the level at this point is the normal level under all operation points.

ρ_w, ρ_s, h_s, h_f and h_w are variables with respect to the drum pressure according to the saturated tables as indicated in [8]. In the simulation, the relationships between these variables as outputs and the drum pressure as input are represented by lookup table blocks. Linearization of the complicated nonlinear drum model to result the proposed simplified linearized drum model, is based on two conditions: $\dfrac{dP}{dt} = 0$ and $\dfrac{dQ}{dt} = 0$. This case is satisfied only when the load demand is constant ($\dfrac{dq_s}{dt} = 0$) as in Iraqi power system because the produced energy does not cover the people needs. Consequently, Eq. (4) is only interested to model the drum water level system and it becomes:

$$(\rho_w - \rho_s)\frac{dV_w}{dt} = q_f - q_s \qquad (8)$$

Substitute (3) in (8):

$$38.88 * (\rho_w - \rho_s)\frac{dL}{dt} = q_f - q_s \qquad (9)$$

The inputs of the process are (q_f and q_s) measured in (t/h) and the output is L measured in mm. Thus, transfer function of this system is given by:

$$L(s) = \frac{G_p}{s}\left(Q_f(s) - Q_s(s)\right) \qquad (10)$$

where $G_p = \dfrac{38.88}{(\rho_w - \rho_s)}$ represents the integrator gain but ρ_w and ρ_s are variables with the drum pressure (P) and therefore, G_p is variable with the drum pressure (the unit load) as shown in Table 1. q_f and q_s are measured in (t/h) and L is measured in mm. It is concluded that the boiler drum water level model changes with the drum pressure.

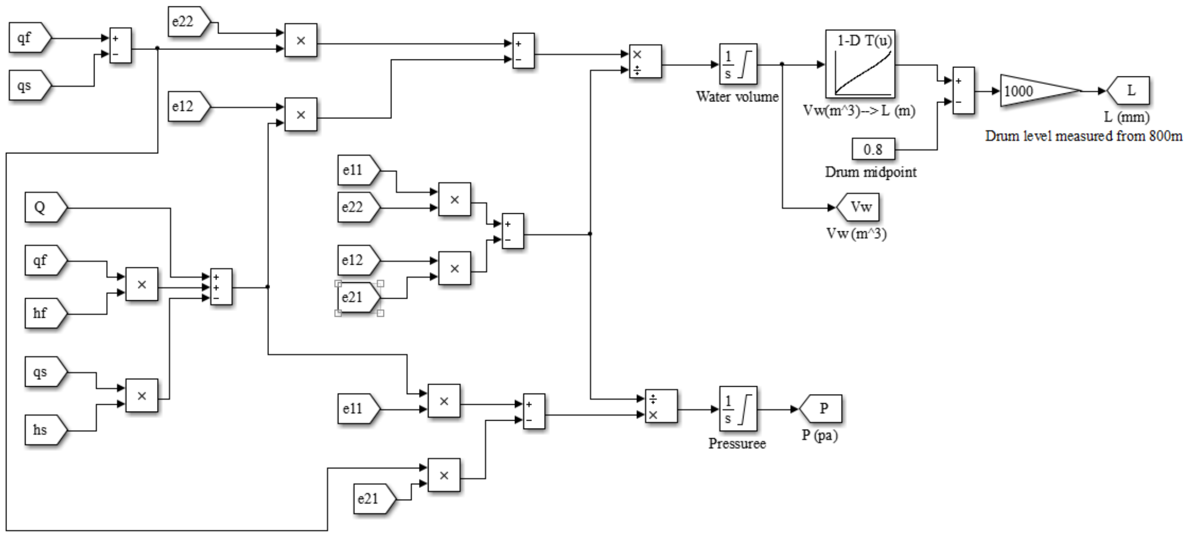

Fig. 4 Simulation of the nonlinear boiler drum system model by MATLAB/Simulink.

Table 1 Change of the integrator gain (G_p) with the drum pressure (P).

P [kgf/cm^2]	ρ_w [kg/m^3]	ρ_s [kg/m^3]	G_p [mm/((t/h).s)]
0	959.03	0.58	0.007454213
10	888.03	5.05	0.008091339
20	851.01	9.852	0.008493636
30	823.37	14.71	0.008834974
40	800.07	19.69	0.009155143
50	779.31	24.834	0.009469473
60	760.18	30.172	0.009786866
70	691.63	54.135	0.011207131
80	675.33	60.982	0.011629386
90	659.03	68.281	0.012093952
100	642.62	76.112	0.012611455
110	625.92	84.576	0.01319769
120	608.73	93.808	0.013874898
130	642.62	76.112	0.012611455
140	625.92	84.576	0.01319769
150	608.73	93.808	0.013874898
160	590.8	103.988	0.014676077

4 Flow Control Valve (FCV) Model

The control strategy on the drum level is carried out by manipulating feedwater flow (valve position) via pulses of closing or opening the valve. The used valve in this plant is a gate valve and operates by three phase AC motor as shown in Fig. 5. The motor is mounted on the valve and geared to the valve stem, so that when the motor operates, the valve will open or close. The input of motor operated valve model is pulse width of closing and opening commands and the output is the feedwater mass flow. The valve transfer function is represented as an integrator with a first order transfer function. The integration function is present because valve position is an integrator of the motor speed. The first order system represents the motor model [3]. The motor operated valve model is here based on assumption that feedwater flow is proportion linearly with valve's gate position. The difficult problem is that the integrator gain of this valve (G_v) is variable with a pressure drop across the valve. However, the typical pressure drop is about 25 kgf/cm^2. In this pressure, G_v represents the flow change of 10 t/h over 1 s pulse width of the open and close commands. Time constant (τ) of the motor is 0.75 s. The valve input ($u(t)$) is pulse width measured in (s) of the open and close commands and the output is the feedwater mass flow ($q_f(t)$) measured in (t/h). So, the transfer function of the FCV can be written by:

$$\frac{Q_f(s)}{U(s)} = \frac{G_v}{s(\tau s+1)} = \frac{10}{s(0.75\, s+1)} \tag{11}$$

5 Validation of the Boiler Drum System Modeling

The validity of simulation results to select the drum water level controller parameters, depends heavily on boiler drum model validity. Thus, mathematical modeling of the boiler drum system is validated by comparison between the practical data and the simulated results. The practical data is extracted from third unit in

Fig. 5 The main feedwater control flow valve used in Nassiriyah thermal power plant.

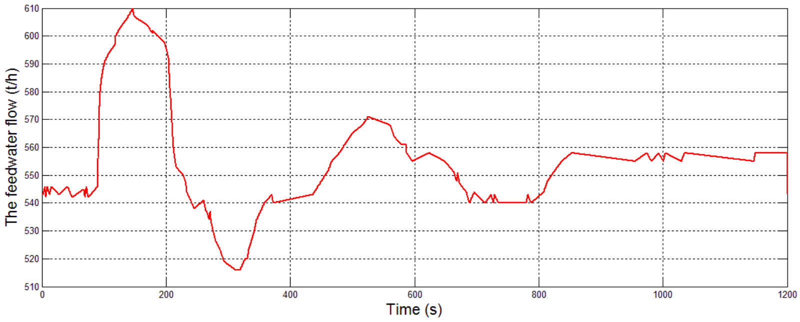

Fig. 6 Plot of the feedwater flow during 1200 s on July 10, 2017 for third unit/NTPP

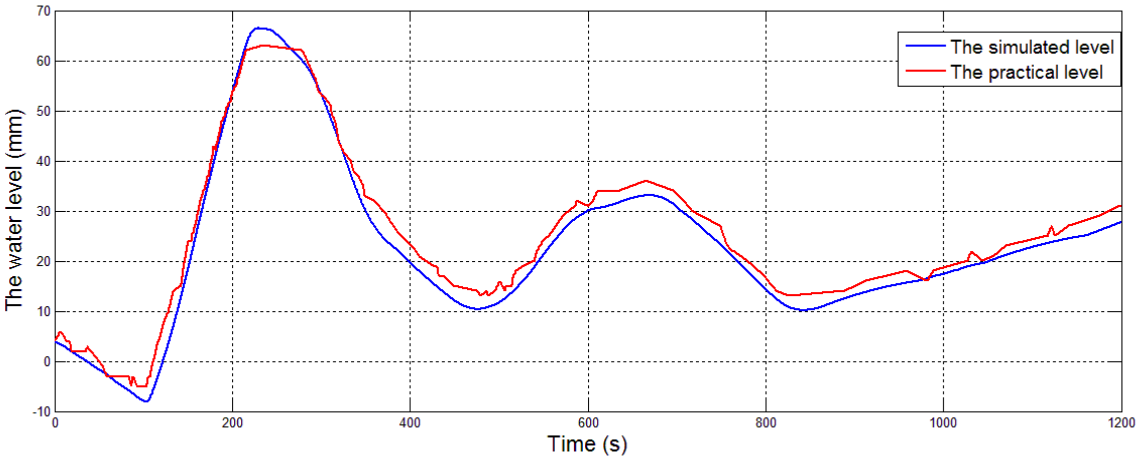

Fig. 7 Plot of comparison between the practical water level response and the simulated water level response by the proposed linearized drum model during 1200 s on July 10, 2017 for third unit/NTPP.

Nassiriyah thermal power plant on July 10, 2017 under 117.5 kgf/cm^2 pressure in the boiler drum and 150 MW active power of the generator. These results demonstrate effect changes of feedwater flow on the drum water level at 552.5 t/h steam flow and 189.7 MW heat flow rate supplied to the risers. Fig. 6 shows plot of the feedwater flow changes during 1200 s. Fig. 7 shows plot of comparison between the practical water level response and the simulated water level response at the linearized drum model. Fig. 8 shows plot of comparison between the practical water level response and the simulated water level response at the nonlinear drum model. As shown in Figs. 6-8, at t=100 s, the drum water level can be expected to rise when the feedwater flow is greater than the steam flow.

It is observed that the nonlinear drum model is more precise in model representation than the proposed linearized drum model. However, the proposed linearized drum model is sufficient to represent the boiler drum system. This conclusion follows that the drum system is analyzed correctly to find the best values of the controller parameters as will indicated later. These results show that delay time for the water level response with respect to changes of the feedwater flow is 12 s. The results of comparison between plant data and water level simulated by the proposed linearized model and the nonlinear model demonstrate the validity of both models.

6 General Structure of the Drum Water Level Controller

A conventional Proportional Integral Derivative (PID) controller is widely used to control flow, pressure, level and temperature in many industrial control systems. Drum water level can be controlled by PID controller which uses feedwater flow as the manipulated variable.

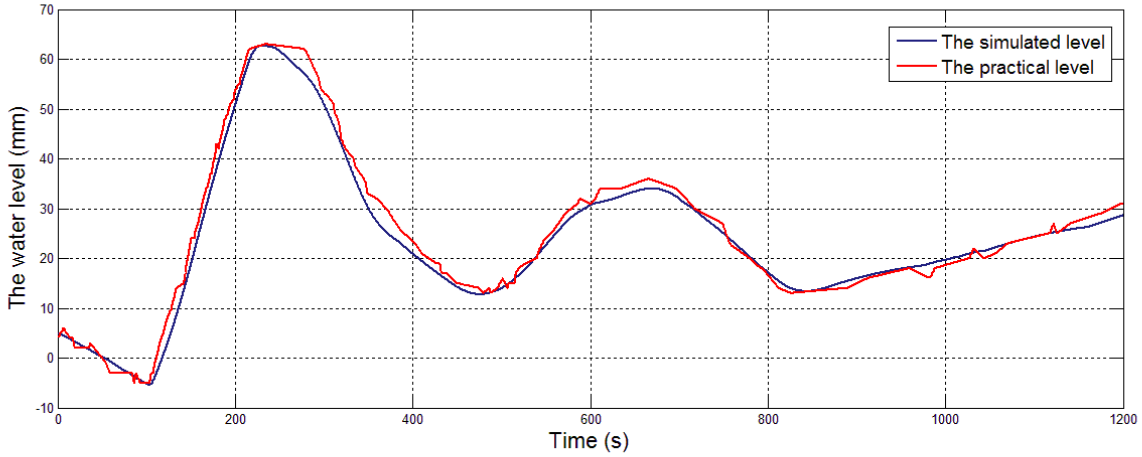

Fig. 8 Plot of comparison between the practical water level response and the simulated water level response by the nonlinear drum model during 1200 s on July 10, 2017 for third unit/NTPP.

Proportional-Integral (PI) terms usually are selected and derivative term is not used because it sensitive to a high frequency measurement noise [2]. Therefore, here, PI terms are selected in the drum water level controller.

Generally, there are two algorithms for PID controller: position algorithm and velocity algorithm. Here, the level controller is based on velocity algorithm because it has many advantages:

- It can avoid integral windup which occurs from accumulation of all past error when the set point changes.
- Simplicity of hardware implementation.

A Programmable Logic Controller (PLC) is one of famous digital controller types. Therefore, the change of controller output ($\Delta u(n)$) for the velocity algorithm of digital ideal PI controller is given by [9]:

$$\Delta u(n) = K_p \left(e(n) - e(n - T_s) + \frac{T_s}{T_i} e(n) \right) \tag{12}$$

where K_p is proportional coefficient, T_s is sampling time, T_i is integral time and n refers to instant time.

In this plant, the main and startup level controllers are based on velocity form of digital PI closed loop control. Process Variable (PV) in each two controllers is the drum water level. The drum water level is controlled by manipulating the feed water flow via opening and closing the main FCV and the startup FCV.

7 The Main Water Level Controller in Drum Boiler

This controller is based on three element level control strategy. This strategy has better stability and performance than one or two element level control strategy because it predicts disturbances of the feedwater flow and the steam flow (load demand) since these disturbances are measurable in addition, the water level is respond to variations of the feedwater flow and the steam flow after a delay time. Moreover, the water level in drum variation is an integrator of difference between the feedwater flow and the steam flow. These elements (or process variables) are the drum water level as controlled variable, the feedwater flow as manipulated variable and the main live steam flow line A as indicated in Fig. 9. This strategy is used the drum water level as a feedback signal and the feedwater flow and the steam flow as feedforward or state signals. There are two control loops: master loop is used to control the water level as controlled variable and slave loop is used to control the difference between feedwater flow and steam flow as state variable to satisfy the mass balance. Therefore, the input signals of this controller are listed below:

a. Calculated signal on the water level in the boiler drum (L) corrected by the drum pressure (P). Range of the water level transmitter in the boiler drum: -315 to 315 mm. The water level in the drum is always measured to the drum's midpoint (800mm), e.g. when the measured water level is 100 mm, actually the water level is 900 mm since 800 mm is selected as reference level.
b. Calculated signal on the main live steam mass flow for line-A (q_{sa}) corrected by pressure and temperature on the same line. Range of the steam flow transmitter: 0-400 t/h.
c. Calculated signal on the feed water mass flow (q_f) corrected by pressure and temperature of the feedwater line. Range of the feedwater mass flow transmitter: 0-800 t/h. Range of the feedwater mass flow transmitter must be 2 times of range of the steam flow transmitter for line-A.
d. Signal from set point. It is recommended that the set point equals 0 mm.

Algorithm of the main water level controller, as indicated in Fig. 10, consists of the following parts:

7.1 Filter

Filtering the input signals here is achieved by time delay for a number of sample periods (T_s) or cycle times. This delay is purposed for stability of the water level and feedwater flow and steam flow due to disturbances which are originated instantly from the drum pressure change through opening or closing the valve. T_s of the PLC is 110ms. Filters delays (T_f) of all input signals (L, q_f, q_{sa}) have been selected as $3T_S$ because it is greater than the disturbances time (about 200 ms). In other hand, greater T_f causes the slower response time for the water level controller. The set point does not need to any filter because it is software variable and is not an input signal coming from the plant.

7.2 Gain and Normalization

The filtered signals from the previous part with the set point are multiplied by appropriate gains. Then, it are scaled from physical values to percent values. The normalized water level ($\hat{L}$) in the drum after the gain stage is calculated by:

$$\hat{L} = \frac{Gx_1 \times L\,(\text{mm}) + 315\text{mm}}{630\,\text{mm}} \times 100\% \tag{13}$$

where Gx_1 is the water level signal gain. L is the water level in the drum measured in mm and displayed in workstation computers. 315 mm is shifted value and 630 mm is span value since range of the water level is from -315 mm to 315 mm.

The set point after gain and normalization stage ($\hat{S}_p$) is calculated by:

$$\hat{S}_p = \frac{Gpm \times S_p\,(\text{mm}) + 315\text{mm}}{630\,\text{mm}} \times 100\% \tag{14}$$

where G_{pm} is the set point signal gain, S_p (mm) is the set point measured in mm and displayed in workstation computers.

The normalized live steam flow from the boiler for line A ($\hat{q}_{sa}$) after the gain stage is calculated by:

$$\hat{q}_{sa} = \frac{Gx_2 \times q_{sa}\,(\text{t/h})}{400\,(\text{t/h})} \times 100\% \tag{15}$$

where Gx_2 is the live steam flow signal gain and 400 (t/h) is span value of the transmitter range.

The normalized feedwater flow ($\hat{q}_f$) after the gain stage is calculated by:

$$\hat{q}_f = \frac{Gx_3 \times q_f\,(\text{t/h})}{800\,(\text{t/h})} \times 100\% \tag{16}$$

where Gx_3 is the feedwater flow signal gain and 800 (t/h) is span value of the transmitter range.

7.3 Calculating Error (E)

The error is calculated by below equation:

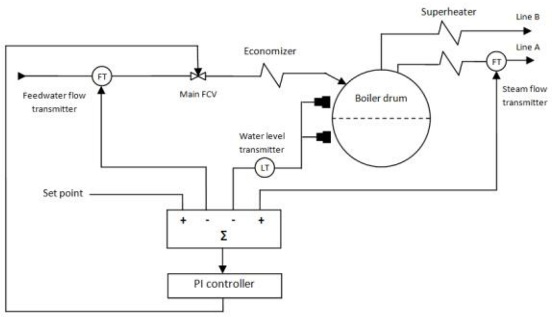

Fig. 9 Structural scheme of the main drum water level controller based on three element control strategy used in NTPP.

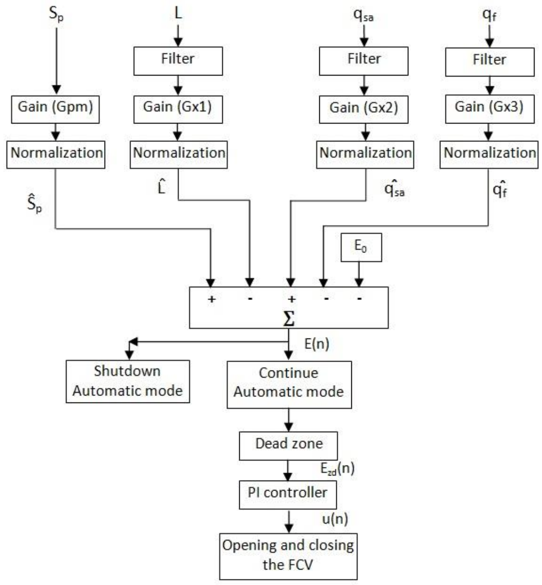

Fig. 10 Block diagram of the main water level controller used in NTPP.

$$E(t) = \hat{S}_p(n) - \hat{L}(n) + \hat{q}_{sa}(n) - \hat{q}_f(n) - E_0 \tag{17}$$

where E_0 is the initial error calculated, when the controller is put into the automatic mode, by below equation :

$$E_0 = \hat{S}_p(0) - \hat{L}(0) + \hat{q}_{sa}(0) - \hat{q}_f(0) \tag{18}$$

It is necessary to present E_0 in (17) because unmeasured difference between the steam flow and the feedwater flow is not take into the account. This different results from blowdown flow, leakage flow, and flow injected by the feedwater pumps to the supperheater steam stages for maintaining their temperature. In addition, the controller does not require that both steam flow and feedwater flow are accurately calibrated at operating point which the controller is put into the automatic mode. However, in order to calculate the error precisely and improve the controller performance at different operating points, the steam flow transmitter and the feedwater flow transmitter must be calibrated precisely. In other word, the steam flow transmitter is calibrated with respect to the feedwater flow transmitter. The controller works well when the controller is put into automatic model and the drum water level is stable or constant, i.e. the global mass balance is satisfied.

7.4 The Controller Shutdown From Automatic Mode

The controller shutdown (trip) from automatic mode occurs in the following cases:

a) Failure of the input signals transmitters (L, q_{sa} and q_f).
b) Lack of power supply voltage in the main FCV.
c) Operating protection "Rise of water level in one of HPH up to the certain protection limit".
d) Controller error signal value (E) exceeding set point of the controller deviation fault (SP_{dev}). The error is compared with SP_{dev} according the algorithm indicated in Fig. 11.

7.5 Dead Zone

The error after the dead zone (E_{zd}) is computed by subtracting or adding dead zone value (Zd) from or to the error, according to below equation:

$$E_{Zd}(n) = \begin{cases} E(n) - Zd & \text{if } E(n) > Zd \\ E(n) + Zd & \text{if } E(n) < -Zd \\ 0 & \text{elsewise} \end{cases} \quad (19)$$

It is necessary to present the dead zone function in the water level controller since the plant actuator is a mechanical valve.

7.6 PI Control Algorithm

In such controller, the ideal velocity PI algorithm is used. The action or control signal, denoted as $u(n)$, is computed according to below equation:

$$u(n) = u(n - T_s) + K_p \left(E_{zd}(n) - E_{zd}(n - T_s) + \frac{T_s\ E_{zd}(n)}{T_i} \right) \quad (20)$$

7.7 Algorithm of Opening and Closing the FCV

The FCV is opened and closed, if $u(n)$ exceeds error thresholds which here are +0.35% for the open operation and -0.35% for the close operation, according to the algorithm shown in Fig. 12.

8 Selection of the Water Level Controller Parameters

There are many parameters of the main water level controller must be tuned to investigate its performance under the transit and steady states. One of the key problems associated with PI control is the difficulty of selecting suitable controller parameters because of the tradeoff between fast dynamic response and steady state performance. So, the controller parameters have been selected according to practical considerations. These considerations are minimizing as possible, a number of the close and open commands to the feedwater flow control valve to extend its lifetime with maintaining the drum water level on a set point.

As mentioned before, Gx_1, Gpm, Gx_2 and Gx_3 are gains of the water level, set point, steam flow of line A and feedwater flow respectively. It is assumed that values of these gains are ranged (0-1) since they refer to weight of effect process variables on the controller operation. Value of Gx_1 is equal to value of Gpm to track the water level about set point precisely. Thus, if values of Gx_1 and Gpm are different, the offset appears between the water level and set point.

Theoretically, value of Gx_2 is equal to value of Gx_3 to satisfy the global mass balance stated previously in (8). However, values of Gx_2 and Gx_3 are convergent because continuous blowdown flow is not taken the account and the measurement of both the feed water flow and the steam flow are not high precision, addition to a leakage of flow on the water-steam lines. In this paper, it is recommended that Gx_2 = Gx_3 and Gx_1 = Gpm.

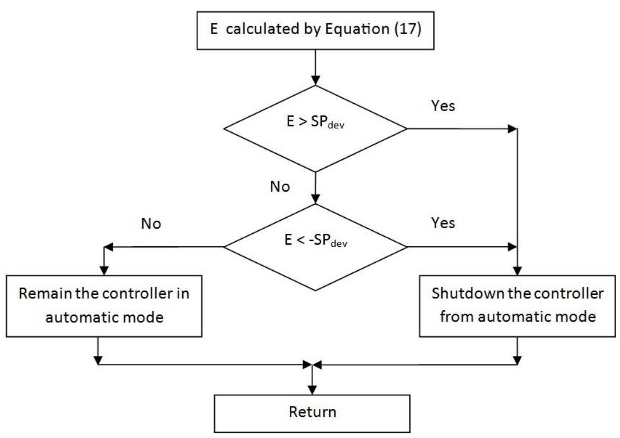

Fig. 11 The flow chart of the main controller shutdown from automatic mode.

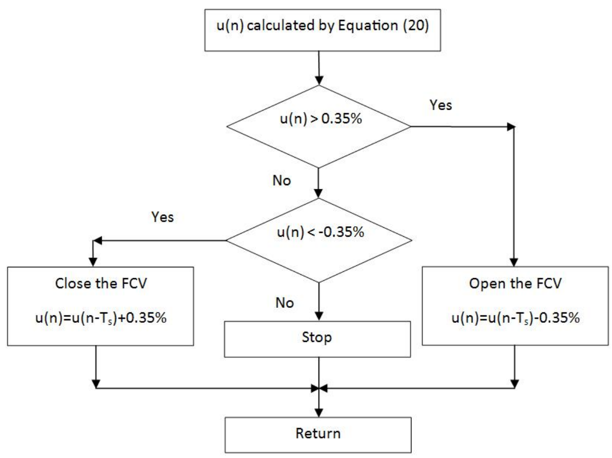

Fig. 12 Flow chart of automatic opening and closing for the main water level controller.

In order to tune the PI controller parameters using the second method of Ziegler-Nichols rules [10], consider the drum control system shown in Fig. 13 without a dead zone function and a comparator of the control signal with error thresholds. For purpose of the linear system analysis, the delay time transfer function ($e^{-t_d s}$) is converted to simple ratio of polynomials functions by bilinear transformation approximation:

$$e^{-t_d s} = \frac{1-0.5t_d\, s}{1+0.5t_d\, s} \tag{21}$$

To make the system analysis easy, time constant of the motor operated valve (0.75 s) is neglected since because it is very small with respect to delay time of the process (about 12 s).

In the second method of Ziegler-Nichols rules, firstly, T_i is set to infinity. The closed loop transfer function denoted as $TF(s)$ for the overall system without an integral action of the PI controller is given by:

$$TF(s) = \frac{-0.5t_d K_p K_L G_v G_p s + K_p K_L G_p G_v}{0.5t_d s^3 + (1+0.5t_d K_p K_q G_v)s^2 + K_p G_v (K_q - 0.5t_d K_L G_p)s + K_p K_L G_p G_v} \tag{22}$$

By Routh's stability criterion, the conditions which satisfy critical stability are given below:

$$K_q > 0.5t_d K_L G_p \tag{23}$$

$$K_p > Max\left(0, \frac{4t_d K_L G_p - 4K_q}{(2K_q - t_d K_L G_p)G_v K_q t_d}\right) \tag{24}$$

To make the second condition shown in (24) as follows:

$$K_p > 0 \tag{25}$$

The first condition shown in (23) becomes as follows:

$$K_q > t_d K_L G_p \tag{26}$$

In fact, $K_q = Gx_2/800 = Gx_3/800$ and $K_L = Gx_1/630 = Gpm/630$ where 800 and 630 are span values for the feedwater mass flow transmitter and the water level transmitter respectively. The above condition shown in (26) becomes as follows:

$$G_{x2} > 1.27t_d G_{x1} G_p \tag{27}$$

Under 150 MW unit load and 117 kgf/cm2 drum pressure, t_d is 12 s and G_p is 0.0137 mm/((t/h).s). When Gx_1 and Gpm are selected as 0.75, critical values of Gx_2 and Gx_3 are 0.1566. In order to ensure the stability when the process parameters (G_p and t_d) change under different operating points, Gx_2 and Gx_3 have been selected as 0.43. In other hand, increasing Gx_2 and Gx_3 will cause increasing the controller response time.

Selecting the controller deviation fault (SP_{dev}) is based on calculation of the absolute maximum error, which can occur by faults. SP_{dev} has been selected as 20% using (13)-(17) since the absolute maximum error 20%, so that the measured water level is ±168 mm, when the set point is 0 mm, both Gx_1 and Gpm are 0.75, and (q_f - q_s) is 0. Actually, ±168 mm level is outside of the normal level operating region where it ranges from -100 mm to 100 mm.

Value of dead zone (Zd) is selected on based the tradeoff between stabilization of motor operated valve and the allowable error limit. Zd has been selected as 0.35% using (13)-(17) since the allowable error limit between the level and the set point (S_p) ranges -3 mm to 3 mm, i.e. the measured water level ranges from (S_p-3) mm to (S_p+3) mm, when (q_f - q_s) is equal to 0 and both Gx_1 and Gpm are 0.75.

The PI controller has K_p and T_i. Selecting these parameter is difficult because the plant is a nonlinear, complex and multivariable process which includes an significant time delay. Furthermore, the water level in the drum is integration of difference between q_f and q_s as stated before in (9). Therefore, all of the tuning methods fail to find the optimum parameters of the controller.

T_i affects significantly on the controller performance at steady state. While K_p affects on the controller performance at both transit and steady states since the used controller is ideal PI form. The integral term is used to eliminate the offset. Increasing T_i leads to increasing the offset. At the same time, decreasing T_i leads to increasing a number of the open and close commands to the valve and deceasing its life time.

Theoretically, K_p is selected based on the condition shown in (25). Practically, K_p is selected based on the maximum allowable error since the plant actuator is a

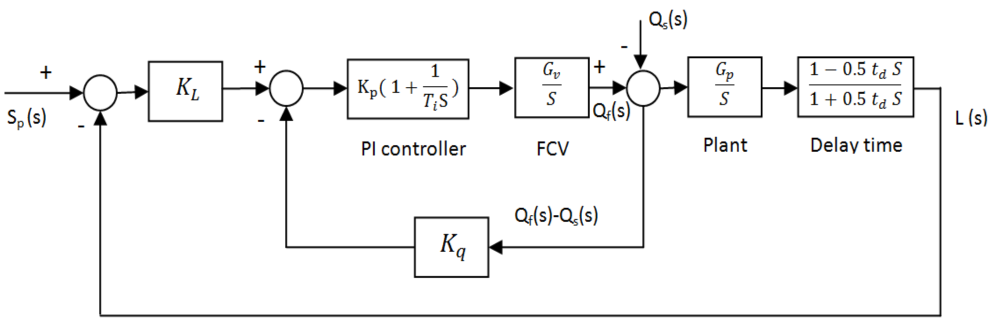

Fig. 13 Block diagram of the drum water level control system.

mechanical valve where increasing K_p leads to increasing a number of the open and close commands to the valve and deceasing its life time. K_p has been selected as 1 since the maximum allowable error offset is 0.7%, which is sum of dead zone value (Zd=0.35%) and the threshold value (0.35%). Then, the valve is opened or closed when $|L- S_p|$ exceeds 6 mm when (q_f - q_s) is equal to 0 and both Gx_1 and Gpm are 0.75 using (13)-(18) which are integrated together to obtain the following equation:

$$(\mathrm{K_p Gx_1}\left(L-\mathrm{S_p}\right)/630)-Zd>0.35\% \tag{28}$$

In the practical view, 6 mm is reasonable value for the water level changes due to present of the noise with the water level signal.

T_i depends on the time delay (t_d) of the process. The water level responds after t_d of opening or closing the FCV and therefore T_i would be greater than t_d to avoid an oscillation about the set point which causes increasing a number of the open and close commands to the FCV. T_i can be selected as 2 times of t_d to ensure avoiding the oscillation under different operating points and eliminating from the offset during a short time. At 150 MW of the rated load, 117 kgf/cm^2 of the drum pressure and t_d is 12 s, so that the proper value of T_i is 24 s.

9 Simulations Results

9.1 Simulation Tests for Selection of Gx_2

Simulation tests are carried out on the drum control system by a step change in the set point from 0 mm to 20 mm at t=100 s during 30 minutes with K_p=1 and T_i=18 to evaluate the controller performance under different values of Gx_2.

Initially, Gx_2 is determined by minimizing the root mean square error (E_{rms}). The simulation results, as indicated in Table 2 and Fig. 14, show that the best value of Gx_2 is 0.75 because E_{rms}, in this case, is the least value with a few number of the open and close commands (N_{cmd} =25) and a small value of the maximum overshoot error (E_{os}=6). It is noted that when Gx_2 is 0 (i.e. the controller becomes one element controller) or less than critical value of Gx_2 (0.1566), the drum level is unstable. The results also show that increasing Gx_2 before the best value will trend the system to more stability with decreasing overshoot and oscillation of the water level about the set point. In other hand, increasing Gx_2 after the best value will cause decreasing the response speed of the level controller.

9.2 Simulation Tests for Selection of K_p and T_i

The tests are carried out by step change in the a set point from 0 mm to 20 mm at t=100 s during 30 minutes. The purpose of these tests is to evaluate performance of the water level controller for different values of K_p and T_i.

Since there are not critical values for K_p and T_i, they are determined by minimizing Cost Function *(CF)* to assess the controller performance for different values of K_p and T_i. Table 3 shows E_{os}, E_{rms}, N_{cmd} and CF for values of K_p (0.5, 1 and 2) and values of T_i (12, 18 and 24 s).

Because all values of E_{os} for different values of K_p and T_i is less than the allowable overshoot error (50 mm). So, the proposed function to calculate CF is given by:

$$\begin{aligned} CF &= 50\% \frac{E_{rms}-\min\left(E_{rms}\right)}{\max\left(E_{rms}\right)-\min\left(E_{rms}\right)} \\ &+50\% \frac{N_{cmd}-\min\left(N_{cmd}\right)}{\max\left(N_{cmd}\right)-\min\left(N_{cmd}\right)} \end{aligned} \tag{29}$$

By applying (29), as in Table 3, the best values of K_p and T_i are 2 and 24 s respectively.

Fig. 15 shows response of the water level controller to a step change in the set point from 0 mm to 20 mm at different values of K_p. It is clear from Fig. 15 and Table 3 that increasing value of K_p causes decreasing the overshoot and the response time and eliminating offset during a short time. This implied that value of K_p affects significantly on fast dynamic response and steady state performance for the controller.

Fig. 16 shows response of the water level controller to a step change in the set point from 0 mm to 20 mm at different values of T_i. It is clear from Fig. 16 and Table 3 that changing value of T_i does not affect significantly on the overshoot and the response time. This implied that value of T_i affects only on steady state performance for the controller.

Table 2 E_{os}, E_{rms} and N_{cmd} for different values of Gx_2 during 30 minutes.

Gx_2	E_{os} [mm]	E_{rms} [mm]	N_{cmd}
0	19.7	11.55	259
0.05	17.99	9.292	180
0.1	16.46	7.85	131
0.2	13.86	6.371	77
0.43	9.68	5.103	38
0.75	6	4.722	25
1.5	2.8	4.826	12
3	1.16	5.671	10

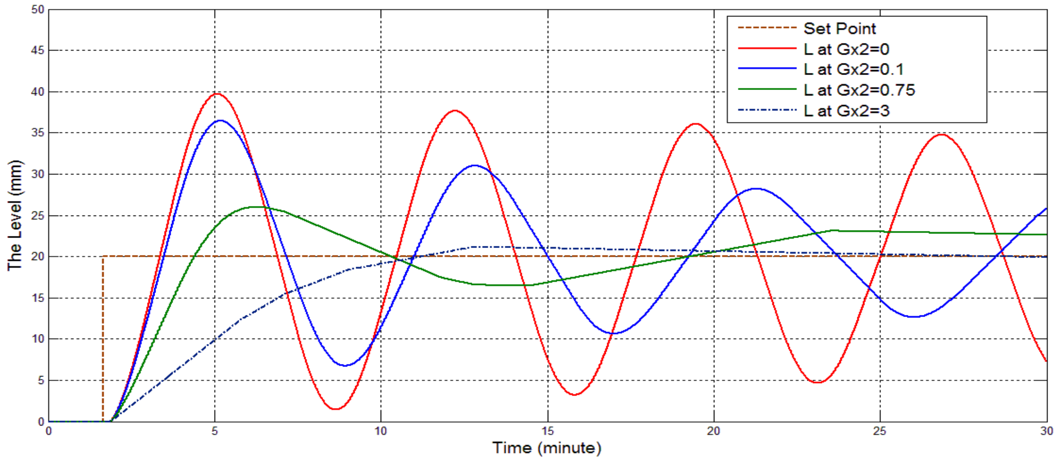

Fig. 14 Response of the water level controller to a step change in the set point from 0 mm to 20 mm at different values of Gx_2.

Table 3 Cost function for different values of K_p and T_i during 30 minutes.

K_p	T_i [s]	E_{os} [mm]	E_{rms} [mm]	N_{cmd}	CF
0.5	12	11.15	5.931	47	83%
0.5	18	11.72	6.564	41	75%
0.5	24	12.05	6.91	35	62%
1	12	8.74	4.684	44	51%
1	18	9.34	5.103	38	40%
1	24	9.52	5.326	33	28%
2	12	6.58	4.08	38	21%
2	18	7.09	4.313	36	19%
2	24	7.32	4.363	31	5%

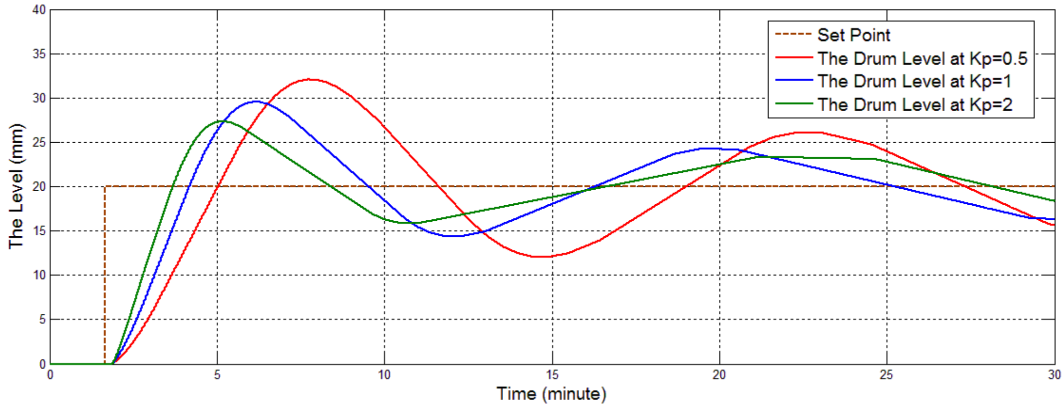

Fig. 15 Response of the water level controller to a step change in the set point from 0 mm to 20 mm at different values of Gx_2.

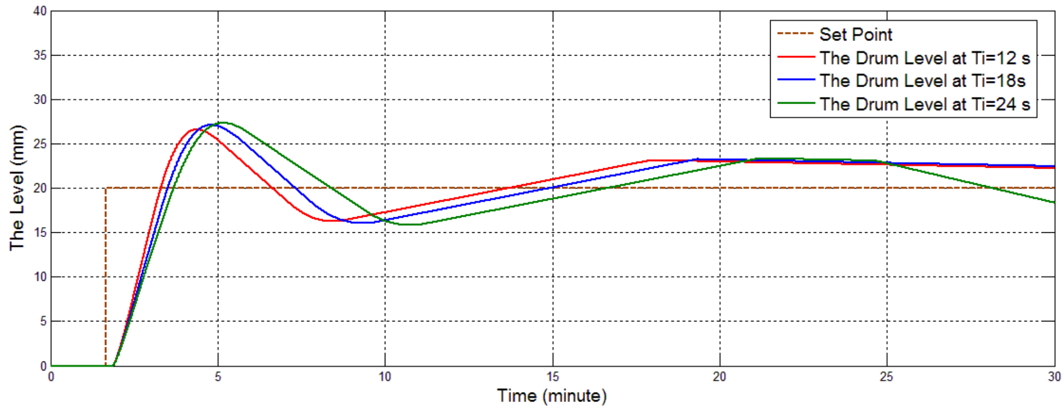

Fig. 16 Response of the water level controller to a step change in the set point from 0 mm to 20 mm at different values of T_i.

10 Experimental Results

The experimental tests are carried out on the main water level controller for third unit in Nassiriyah thermal power plant on July 10, 2017 under 117 kgf/cm^2 of the drum pressure and 150 MW of the unit load. The experimental results demonstrate effect of T_i on performance and stability of the drum water level. Fig. 17 shows the drum water level and the set point (37mm) for 25 minutes at different values of T_i. Table 4 shows evaluation of the water level controller performance at different values of T_i during 25 minutes. It can be seen from Table 4 that E_{rms} increases with increasing value of T_i. This confirms the simulation results shown in Table 3 and Fig. 16. In other hand, when T_i increases, a number of the close and open commands (N_{cmd}) to the valve will decrease. Consequently, increasing T_i leads to increasing lifetime for the mechanical and electrical parts of the valve. However, at T_i=18 s, E_{os} is less than the two other. Thus, the best value of T_i is 18 s since the E_{os} is small and the N_{cmd} is reasonable value.

11 Conclusions

In this paper, the drum water level referring to 210 MW power unit for Nassiriyah thermal power plant, has been modelled and its controller operation has been studied. Firstly, the drum water level process has been modelled based on first principles by two models: the proposed simplified linearized model and the complicated nonlinear model. Then, a comparison between the extracted practical plant data and the water level results simulated by the two models demonstrate the validity of both models with very good approximations. The results also show that the complicated nonlinear drum model is more precise in

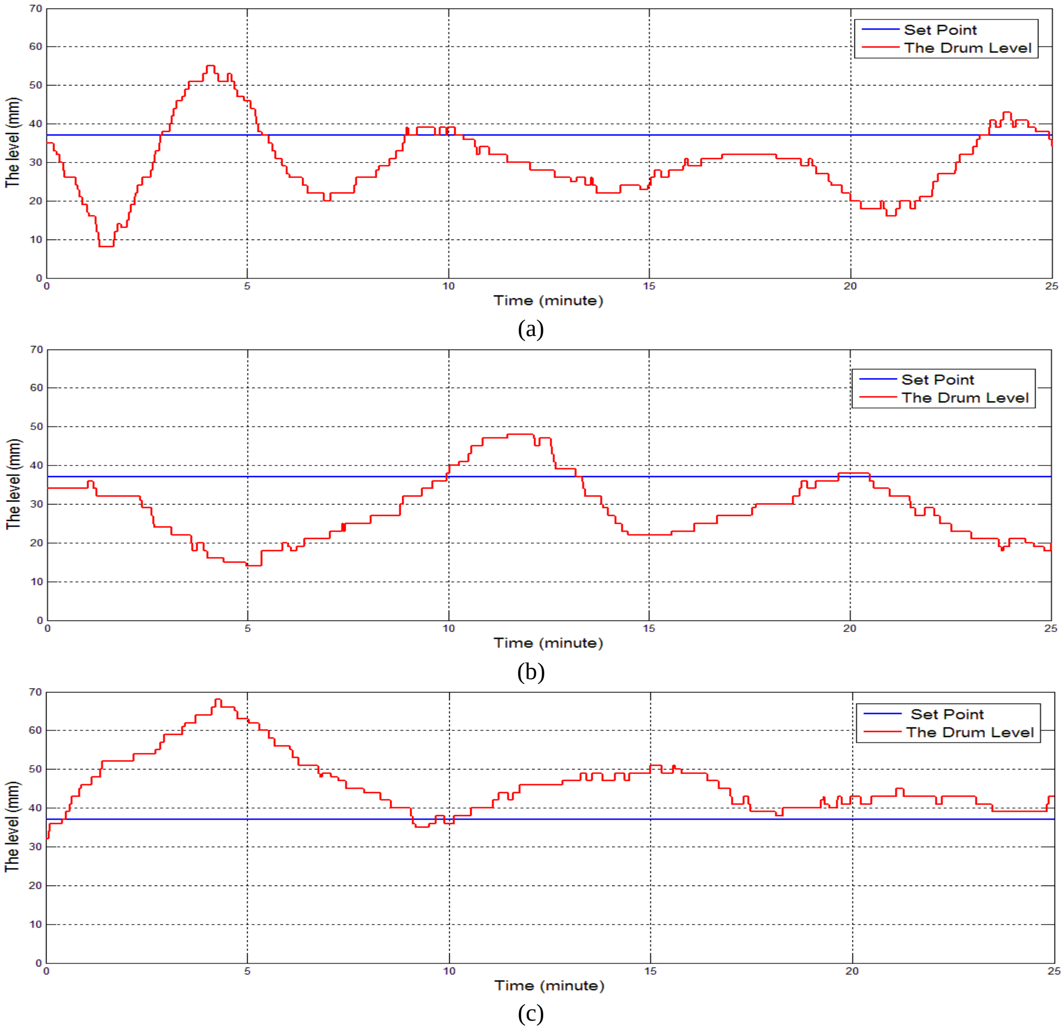

Fig. 17 Performance of the water level controller at different T_i; a) T_i =12 s, b) T_i =18 s, and c) T_i =24 s.

Table 4 Evaulation of the water level controller performance at different T_i during 25 minutes.

T_i [s]	E_{rms} [mm]	E_{os} [mm]	N_{cmd}
12	11.5	29	242
18	11.8	23	149
24	11.89	31	87

model representation than the proposed simplified linearized drum model. However, the proposed simplified linearized drum model is sufficient to represent the boiler drum system. Secondly, PI controller based on three element water level control strategy and used in this plant, has been described and simulated by MATLAB/Simulink. The controller parameters have been selected according to practical considerations. These considerations are minimizing as possible, a number of the close and open commands to the feedwater flow control valve to extend its lifetime with maintaining the drum water level on a set point. The controller has been tested to evaluate its performance for different values of K_p, T_i, gain of steam flow signal (Gx_2), and gain of feedwater flow signal (Gx_3). Firstly, the results show that selection of K_p is difficult because of the tradeoff between fast dynamic response and steady state performance. Secondly, the results show selection of T_i does not affect significantly on fast dynamic response and affects only steady state performance. Finally, the results show that selection of Gx_2 and Gx_3 plays an important role in stability of the drum water level.

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