Optimization-based PID Controller Design with Gain Scheduling for the Drum Boiler Level Control of the Industrial Combine Cycle Plant

Viriya Kongratana, Badin Suthat and Napasool Wongvanich*

***Abstract*— This work aims to present an application of water level control system for a three-element cascade drum boiler with a PID controller. The PID control value was divided into two control ranges, including peak mode operation during high power consumption and off-peak mode operation during low power consumption for a combined cycle power plant. The feedforward part was the flow rate, while the feedback part was the water level in the drum boiler. Such variables consisted of steam output flow rate, feed water flow rate and water level in the drum boiler. The optimization method was applied for calculating the parameters of the water level controller in the drum boiler. As a result, it was found that the PID controller with divided control phases was able to clearly control the water level of the drum boiler better than a single PID controller. It was able to handle transient and rapid processes very well. For example, shrink and swell effects of water in a drum boiler caused by the fluctuation of the pressure inside the boiler. This method could be used practically for controlling the water level in power plant drum boilers.**

***Index Terms*— Three-element cascade drum boiler level control system, Gain scheduled PID, Peak mode operation, Off-peak mode operation, Combined Cycle Cower Plant (CCPP).**

I. INTRODUCTION

ELECTRICAL power generation is one of the cornerstones that drives the global economy. Natural gas is one of the main fuels used for power generation, with 61.75% of the power plants operating from natural gas in Thailand [1] by using Combine Cycle Power Plants (CCPP). The fuel costs of a power plant comprise a gargantuan 75% of the total costings throughout the machine's life cycle [2], motivating the developments of cost-effective models and operations.

Bang-Pa-In Power Plant Project 1 was a combined cycle power plant (CCPP) that uses natural gas as a fuel to generate electricity. There were 2 systems working together, including Gas Turbine (GT) and Steam Turbine (ST) as a same system by entering hot gas from the gas turbine into the furnace of the Heat Recovery Steam Generator (HRSG) to boil water, to generate steam, and then to drive the steam turbine for starting operation. Bang-Pa-In power plant sold electricity to the Electricity Generating Authority of Thailand (EGAT) and the rest of the electricity and steam to other operators.

Bang-Pa-In Power Plant Project 1 was commissioned to supply electricity into the grid system by the National Control Center (NCC). It was ordered to distribute power of 90 MW during the Peak mode operation and 55 MW of power during Off-peak mode operation. In both Peak & Off -Peak Mode Operations, the power plant needed to have electricity and steam supply to other operators as well (according to the steam purchase agreement between Bang-Pa-In power plant and other operators). The difference between Peak and Off Peak Mode Operation was the amount of Exhaust Gas Flow flowing into the Heat Recovery Steam Generator Boiler (HRSG). The Peak mode operation conditions had more exhaust gas flow than Off-Peak mode operation. Thus, the amount of Exhaust Gas Flow flowing into HRSG at different flow rate caused different conditions of water level control in HRSG as well.

In this research, the CENTUM VP Version 5.02.00 of YOKOGAWA automatic control system, was selected by applying with the PID controller of control system for the three-element cascade water level control in the drum boiler for a combine cycle power plant. The objectives were to keep a constant water level in the drum boiler and to correct the impacts from transient processes rapid changes in processes. For example, shrink and swell effects of water inside a drum boiler, which directly affected the malfunction of the controller [3]. The results of the experiment demonstrated that the three-element cascade water level control in the drum boiler could control the water level within the specified limits according to the target value, which was in accordance with the presented principles.

This work presented an application of a three-element cascade water level control system with a PID controller for controlling the water level in the drum boiler of a combined cycle power plant. The variables consisted of steam output flow rate, feed water flow rate and water level in the drum boiler [4]. The study applied the optimization method to calculate the parameters of the water level controller in the drum boiler, which operated on a distributed control system,

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with a design and selection of suitable measuring devices. In particular, the study looks at the design of a gain scheduling cascade PID controller for controlling the water level in the drum boiler in the Peak mode and Off-Peak mode operating conditions.

II. COMBINE CYCLE POWER PLANT (CCPP)

A combined cycle power plant used natural gas as a fuel to generate electricity. There were 2 systems working together, including Gas Turbine (GT) that generated power using the Brayton Cycle and the Steam Turbine (ST) that generated power using the Rankine Cycle, by entering hot gas from the gas turbine into the furnace of the Heat Recovery Steam Generator (HRSG) to boil water, to generate steam, then to drive the steam turbine for starting operation [7]. The operation of the combined cycle power plant (CCPP) was consistent with the combined cycle as shown in Figure 1.

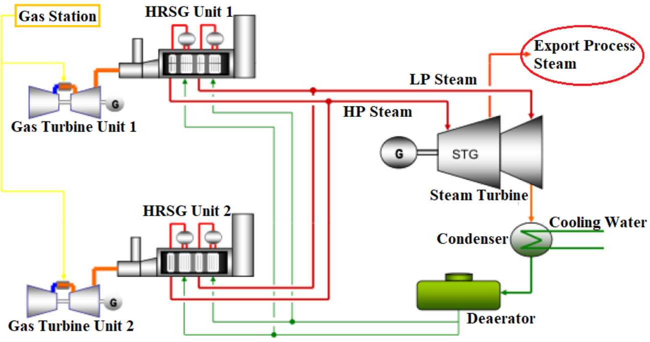


Fig. 1. Combined cycle cogeneration power plant (CCPP).

III. CAUSES AND PROBLEMS OF WATER LEVEL CONTROL IN DRUM BOILERS

Controlling the water level in drum boilers for a combined cycle power plant was a critical aspect of the power generation process. Normally, the boiler and steam turbine control systems needed to be controlled according to the amount of water inside the drum boiler, which the water level must be controlled to be in the designed range only. If the water level is too high, moisture will mix with the steam entering the steam turbine. This was the main cause of damage to parts of the steam turbine. If the water level of the drum boiler is below a certain threshold, it will affect the wall of the water supply pipe to the boiler, which may cause cracking due to overheating. This problem would affect the power generation process to stop, increase the cost of maintenance and repair, and may cause injury or death of personnel. Usually, while the boiler water level was below or above the threshold, the boiler control system had a system form damage that may occur to equipment and machinery in the system. The protection system would stop the operation of the combustion system and the water supply system to the boiler respectively. To control the water level inside the drum boiler, there were 2 problems of the control as follows.

A. *Swell Effect of Drum Boiler*

Water expansion was a characteristic of the increased water level in a large quantity. This problem was most common during the start-up boiler or in case of a having rapid increase in steam consumption causing the rapid and significant drop of pressure inside the boiler, which would make the water boil easier. While the pressure dropped, more water would be boiled. This caused the water level in the drum boiler to increase, even though the water was not added at all. Also, when the water level exceeded the limit, the steam boiler protection system sent signals to the gas turbine power generation unit to stop production, in order to protect the equipment in the system from damage and danger that may occur.

B. *Shrink Effect In Drum Boiler*

Water shrinking effect was a symptom in contrary to water swell effect. When there was a quick stop of using of steam, it caused the pressure in the boiler to increase the steam pressure rapidly. The higher pressure would affect huge decrease in the water level in the boiler. This made the water level meter in the drum boiler to detect that the significant drop of water level. When the water level was below a certain limit, the steam boiler protection system would send signals the gas turbine power generation unit to stop production, in order to prevent possible future damage to the equipment.

IV. MATHEMATICAL MODELLING OF BOILER DRUM

It is well known that mathematical modeling, and simplified modeling in particular, is paramount for the design of effective control system [8]. In this respect, the mass and energy conservation equations are written for the drum in its entirety. The entire contents of the drum are assumed to be in the saturation state.

A. *Mass and Energy Balance*

The boiler drum level ld responds in an integrating manner to the steam flow Fd and feed water flow Few. Basically, the drum model describes the dynamics of drum water volume Vdw in terms of the mass and energy conversion equations [5]. A separate relationship between Vdw and ld is derived then from the geometry of the drum and this equation is solved using the Newton-Raphson method to obtain ld. The mass and energy balance equations for the boiler drum are derived as follows.

Mass Balance

Rate of change of mass of steam and water in the drum = Feed water flow to the drum – steam flow from the drum

$$\frac{d}{dt}\left[(V_d - V_{dw})\,\rho_d + V_{dw}\rho_{dw}\right] = F_{ew} - F_d \tag{1}$$

Energy Balance

Rate of change of energy of steam and water in the drum = Total energy of steam and water mixture after leaving the water walls - Energy of drum water - Energy of drum steam

$$\frac{d}{dt}[(V_d - V_{dw})\,\rho_d h_d + V_{dw}\rho_{dw}h_{dw}] = F_D h_w - (F_D - F_{ew})h_{dw} - F_D h_d \tag{2}$$

The differential equations obtained are

$$\frac{d\rho_d}{dt} = \frac{1}{q_2 q_4 \rho_{dw}} \{\rho_d F_{ew} - \rho_{dw} F_d + X_q F_D(\rho_{dw} - \rho_d)\} \quad (3)$$

$$\frac{dV_{dw}}{dt} = \frac{1}{q_4 \rho_{dw}} \{(1 + q_3)F_{ew} - q_3 F_d + X_q F_D\} \quad (4)$$

The drum level ld is computed using Newton-Raphson Method.

$$l_d(k+1) = l_d(k) - \frac{f(l_d(k))}{f'(l_d(k))} \quad (5)$$

Table 1: Nominal values of Boiler Drum variables

Variables	Description	Value	Unit
ρ_d	Density of drum steam	8.221 x 10^{-5}	kg/cm^3
ρ_{dw}	Density of water in drum	63.097 x 10^{-5}	kg/sec
F_{ew}	Feedwater flow	163.5023	kcal/kg
h_{ew}	Enthalpy of feedwater	131.97	kg/sec
F_d	Steam flow from drum	175.014	kg/sec
l_d	Drum level	88.90	cm
p_d	Steam pressure in the drum	176.8	kg/cm^2
T_d	Saturated steam temperature	354	°C
X_q	Steam quality	0.95	-
δh_d	Gradient of drum steam enthalpy	-657954.52	kcal-cm^3/kg^2
δh_{dw}	Gradient of water enthalpy at drum Conditions	1128547.11	kcal-cm^3/kg^2
$\delta \rho_{dw}$	Gradient of drum steam density	-2.0132	-
V_d	Volume of drum	40185469.46	cm^3
V_{dw}	Drum water volume	20092734.73	cm^3
l	Length of drum	1500	cm
r	Radius of drum	88.9	cm

V. MEASUREMENT AND CONTROL

The drum boiler for the combined cycle power plant differed from the general drum boiler as it was a high pressure drum boiler. The inside of the drum boiler was composed of 2 liquids, including water and steam at the saturated state, which had different and vary tightness according to the pressure of the boiler. Therefore, the measurement of variables in the process, for example, water level of the boiler, steam output flow rate and the feed water flow rate into the drum boiler, was necessary to compensate for the altered water and steam tightness for accurate measurements by installing a water level monitor inside the drum boiler as shown in Figure 2.

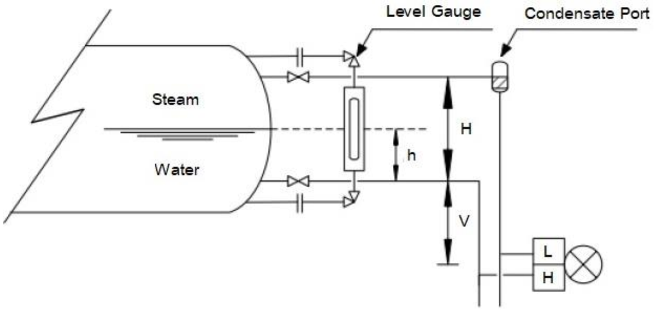


Fig. 2. Water level measurement of the steam boiler using a differential pressure sensor device

A condensation device for steam or water bulb at the low pressure connection was provided as a comparison. While operating, the steam inside the bulb would condense, causing the water in the bulb (Condensate Port) to remain constant level at all times. The difference of pressure was measured from the difference between the water level in the bulb and the water level in the drum boiler. Aldo, the measured difference of pressure would be a reverse of the water level in the boiler. That was, the difference of pressure would reach its highest level when the water level dropped to the lowest level. The pressure difference would reach zero when the water level in the drum boiler was higher than the top junction or as high as the water level in the bulb.

When considered Figure 2, the pressure on the L side of the pressure difference gauge was caused by the sum of the internal static pressure plus the pressure generated by the water in the L-side pipe.

$$PL = \rho agV + \rho agH + Pd \quad (6)$$

The pressure on the H side of the pressure difference gauge was caused by the sum of internal static pressure, pressure exerted by the pressure of the steam, inner water height and the height arising from water in the pipe H side.

$$PH = \rho agV + \rho wgh + \rho sg(H - h) + Pd \quad (7)$$

Therefore, the pressure difference that was caused at the pressure difference measuring device was

$$\Delta P = P_H - P_L \quad (8)$$

$$\Delta P = \rho_a gV + \rho_w gh + \rho_s g(H - h) + P_d - \rho_a gV - \rho_a gH - P_d$$

$$\Delta P = \rho_w gh + \rho_s gH - \rho_s gh - \rho_a gH$$

$$\Delta P = gh(\rho_w - \rho_s) - gH(\rho_a - \rho_s) \quad (9)$$

$$h = \frac{\Delta P + gH(\rho a - \rho s)}{g(\rho w - \rho s)} \quad (10)$$

Where;

Pd was the static pressure in the drum boiler (barg)

H was the height between the top and the bottom junction (mm)

h was the height of the water from the bottom junction (mm)

V was the height of the bottom height of the drum boiler to the pressure difference sensor (mm)

g was the gravitational value (m/s2)

ρ_s was the density of saturated steam inside the steam boiler (kg/m3)

ρ_w was the density of saturated water inside the drum boiler (kg/m3)

ρ_a was the density of the condensed water in the condensing device (kg/m3)

ΔP was the pressure difference that occurred at the pressure difference measuring device (mmH_2O)

The main objective of this research was to control the water level in the high pressure drum boiler within the specified limits by applying a three-element cascade water level control system in a drum boiler for power plants with a distributed controller. The variables consisted of steam output flow rate, feed water flow rate and water level in the drum boiler.

The water level measuring and controlling of the high pressure drum boilers of the Bang Pa-in Cogeneration Power Plant was controlled by the automatic control system CENTUM VP Version 5.02.00 of the YOKOGAWA, which had a graphic showing the measure and control of the water level of the steam boiler as shown in Figure 3.

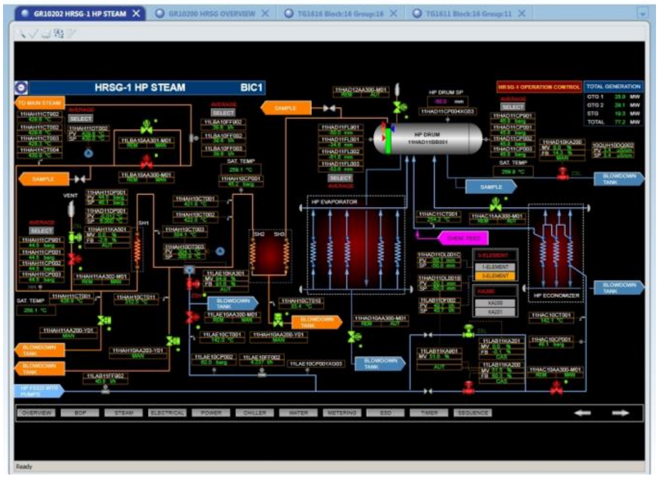


Fig. 3 Graphic display of water level measurement and control of high pressure drum boiler.

VI. PID CONTROL

The most widely used structure of controller for process value control was a Proportional-Integral-Differential controller, known for short as PID controller [6], which was easy to understand and stable. The value to be calculated was the error value, which was obtained by the difference of the variable in process and the set point value to be controlled. The controller would try to minimize the error value by modulating the process input signal. The performance of the controller depended on the mentioned parameters. Therefore, the method of calculating the most suitable parameters of a controller for maximum stability of the control system was called PID control tuning. This was a critical problem in optimizing control parameters, which was called a method of tuning parameters. Basically, the most common method for determining the appropriate control parameters was usually the method of Ziegler-Nichols, etc. The approach taken in this paper is the optimization approach which is described in the subsequent sections.

A. *Optimization based PID tuning*

The control of the Drum level rise is achieved by solving the optimization problem [7]:

$$\min \int_0^{Tf} |t(L_{d,set} - L_{d,real})|dt \qquad (11)$$

subjected to the constraints: $0 < u_{mass} < u_{mass,max}$

Where $L_{d,set}$ represents the drum level set point, $L_{d,real}$ is the current level, u_{mass} represents the mass flow required to keep the level at the desired set point. The required mass flow is, in turn, controlled by adjusting the control valve position, which solves the optimization problem online:

$$\min \int_0^{Tf} |t(M_{req} - M_{real})|dt \qquad (12)$$

subjected to the constraints: $0 < u_{valve} < u_{valve,max}$

Where M_{req} is the required mass flow to the drum and u_{valve} is the control valve position. In terms of the implementation, an engineer then enters the Distributed Control System (DCS) the desired level drum to the level set point.

B. *Cascade control*

Cascade control was one of the most common control techniques in process control. It was often found in a control system with two serial systems. The factor of disturbance in the case of slow response of noise referred to the Process Variable)PV(that was likely to deviate from equilibrium longer. The cascade control structure was composed of 2 nested control loops. The additional loop was commonly referred to as the secondary loop as shown in Figure 4.

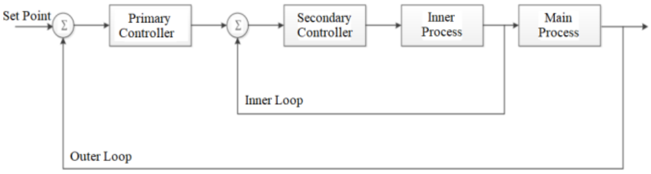


Fig. 4. Diagram block of the cascade control structure

The water level of the high-pressure drum boilers of Bang-Pa-In Cogeneration Power Plant was controlled in a cascade way, which had a graphic showing the measure and control of the water level of the cascade high pressure drum boiler as shown in Figure 5.

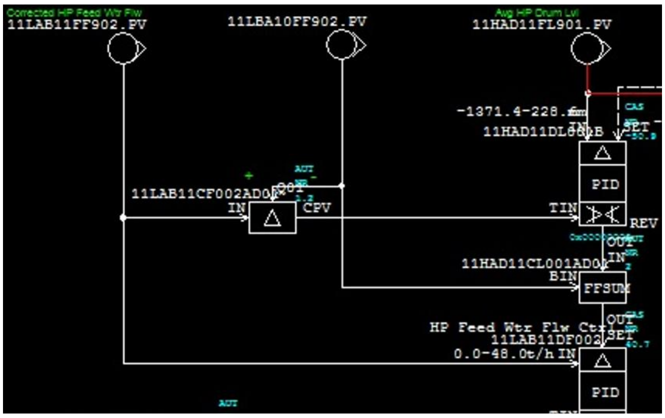


Fig. 5. Graphic showing the water level measurement and control of the cascade high pressure drum boiler

VII. PID CONTROL SYSTEM DESIGN WITH GAIN SCHEDULE

Bang-Pa-In Power Plant Project 1 was commissioned to supply electricity into the system by the National Control Center (NCC). It was ordered to distribute power of 90 MW during the Peak mode operation and 55 MW of power during Off-peak mode operation. The difference between both Peak and Off-Peak Mode Operation was the amount of the load of Gas Turbine. For the Peak mode operation condition, both Gas Turbines would supply approximately 45 MW of load per each gas turbine. For the Off-peak mode operation condition, both Gas Turbines would supply approximately 25 MW of load per each gas turbine.

For another difference of loading of the Gas Turbine at 45 MW and 25 MW, apart from the power input into the system, there was also the amount of Exhaust Gas Flow flowing into the heat recovery steam generator (HRSG). For the Peak mode operation condition, there would be more Exhaust Gas Flow than those of the Off-peak mode operation. Thus, the different amount of Exhaust Gas Flow flowing into HRSG resulted in the different condition of water level control in HRSG as well.

The problem arising with the Bang-Pa-in Power Plant Project 1 was the issue of controlling water level of the three-element cascade type high pressure drum boiler with a PID controller. The water level could be controlled to be in the set value only with one condition during the Off-peak mode operation according to Figure 6. On the other hand, the operation in the conditions of the Peak Mode Operation could not control the water level to be within specifications as depicted in Figure 7.

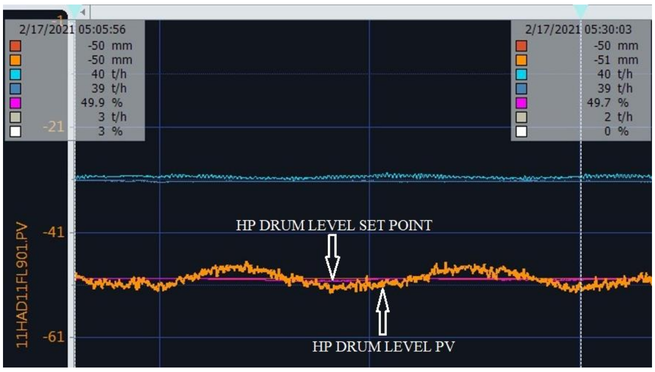


Fig. 6 Water level control of high pressure drum boiler during Off-Peak Mode Operation using PID control parameters set 1

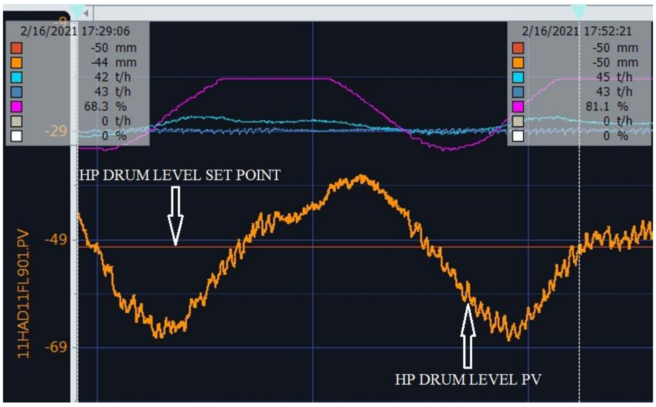
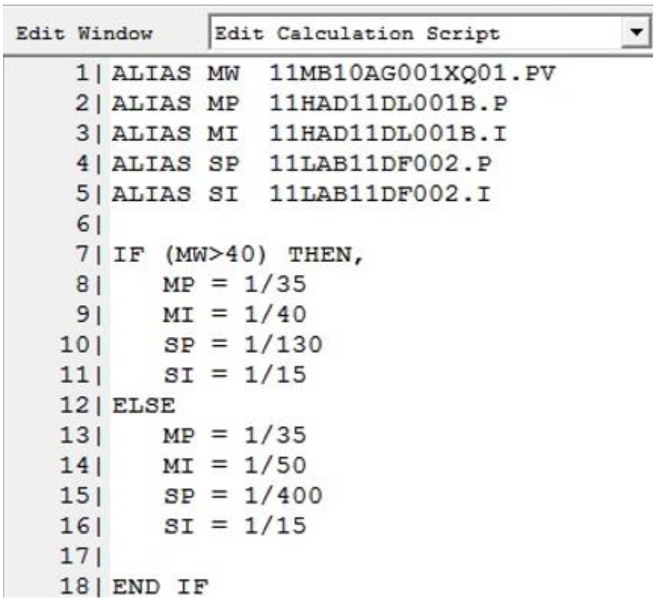


Fig. 7 Water level control of high pressure drum boiler during Peak Mode Operation using PID control parameters set 1

To solve this problem, two sets of PID controllers are designed. The first PID controller is designed to work on the Off-Peak Mode Operation. The Second Set of PID controller is designed to work during Peak Mode. Changing the PID variable value required no additional equipment installation; only additional programming in the CENTUM VP Version 5.02.00 of YOKOGAWA distributed control system is required. Figure 8 shows the implementation on the YOKOGAWA system.

Table 2: PID variable value that was designed into two suitable control sets for Off-Peak Mode Operation and Peak Mode Operation.

PID Parameter		PID set 1 for Off-Peak Mode Operation	PID set 2 for Peak Mode Operation
Primary Loop	KP	1/35	1/35
	KI	1/50	1/40
	KD	0	0
Secondary Loop	KP	1/400	1/130
	KI	1/15	1/15
	KD	0	0



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ALIAS MW  11MB10AG001XQ01.PV
ALIAS MP  11HAD11DL001B.P
ALIAS MI  11HAD11DL001B.I
ALIAS SP  11LAB11DF002.P
ALIAS SI  11LAB11DF002.I

IF (MW>40) THEN,
   MP = 1/35
   MI = 1/40
   SP = 1/130
   SI = 1/15
ELSE
   MP = 1/35
   MI = 1/50
   SP = 1/400
   SI = 1/15

END IF
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Fig. 8 Writing conditional functions to select the appropriate PID variable under the conditions of Off-Peak Mode Operation and Peak Mode Operation.

VIII. EXPERIMENTAL RESULTS

As a result of this experiment, the PID controller was divided into two sets of controls. The Peak Mode Operation applied the first set of PID variables. Meanwhile, the Off-Peak Mode Operation applied the second set of PID variables. From the results of the experiment, it could be seen that dividing the PID control variable into two sets allowed the water level of the high pressure drum to be controlled at the target value of both operating conditions as shown below.

A. *Off-Peak Mode Operation*

The Off-Peak Mode Operation did not modify the PID parameter in any way because the original PID value)PID control parameters set 1(could control the water level to be at the specified value as shown in Figure 9

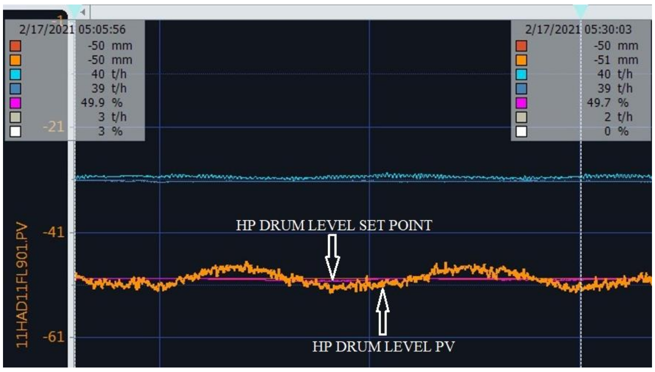

Fig. 9 The PID control variable set 1 that could control the water level to be at the specified value under the conditions of Off Peak Mode Operation.

B. *Peak Mode Operation*

For the Peak Mode Operation, PID parameters had been adjusted to better control the water level of the High-Pressure Drum boiler. Therefore, the PID parameters had been adjusted from the PID control variable set 1 as shown in Figure 10 to the PID control variable set 2 to be able to control the water level as specified in Figure 11.

Before the experiment

PID control parameters set 1 could not control the water level to be at the specified value under the conditions of the Peak Mode Operation as shown Figure 10.

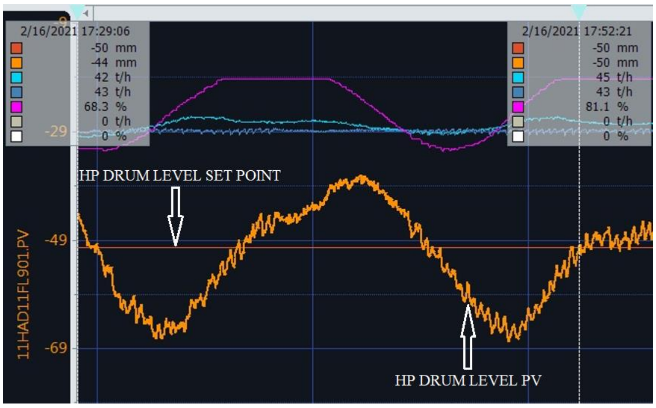

Fig. 10 PID control parameters set 1 that could not control the water level to be at the specified value under the conditions of the Peak Mode Operation.

After the experiment

PID control parameters set 2 could control the water level to be at the specified value under the conditions of the Peak Mode Operation as shown Figure 11

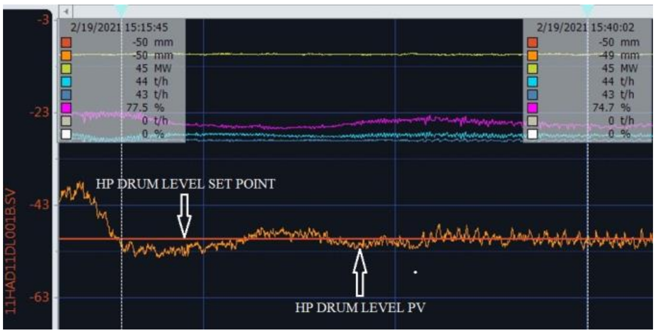

Fig. 11 PID control parameters set 2 that could control the water level to be at the specified value under the conditions of the Peak Mode Operation.

IX. CONCLUSION

This work designed and applied the optimization based cascaded PID controller, augmented with gain scheduling, for a three-element drum boiler in an industrial combine cycle power plant. A gain schedule PID controller was designed that specified one set of PID gains to operate in an Off-Peak Mode Condition, and another set of PID gains to work in Peak Mode Condition. Experimental results show that this configuration was able to control the water level of the high-pressure drum boiler to be at a specified value in both conditions correctly and precisely. This was very useful in operating the machine to reduce machine errors, which might damage the Bang-Pa-In Power Plant Project 1 from stopping the electricity distribution suddenly due to the problem of unable to control the water level to be at the set point value.

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