A Multivariable Self-tuning Controller for a D-type Water Tube Industrial Boiler

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Abstract: The present paper focuses on the development of a control system strategy on medium size industrial boilers (up to 1 MW) with the aim of having safe and efficient operation for the boiler itself. The class of the considered boiler is D-type water tube boiler. The basic plant model is based on Åström and Bell nonlinear dynamic model with simple adaptation due to specific geometries and physical constraints. The control system is mainly a combination of a pressure control loop and a three-element level controller. The pressure control loop here proposed consists of a gain scheduling PID control strategy to operate on heat power in order to keep the pressure at its desired value. The three-element level controller is a two-loop cascade control with feed forward water aimed at correcting the mismatch between the demand (steam flow) and feed water flow: level variation must be considered during this process because of the non-minimum phase behaviour of the level. Due to switching behaviour of gain scheduling approach, an adaptive control rule is also investigated in order to simplify the overall control structure and alleviate the adverse effects of the switching among many controllers in industrial applications.

1 INTRODUCTION

Steam has unique properties that are extremely important in many industrial processes, for a wide variety of completely different applications. It can be used to produce electricity but it can be directly used in industrial processes for specific thermos-physical transformation or for cleaning. Steam is basically recycled, in a closed loop, from steam to water and then back to steam again, all in a manner that is nontoxic in nature. One of the most effective parameters on ultimate cost of the end product is the amount of heat required to produce the steam. This heat must come from an energy source, and this varies significantly, often based on the plant's location in the world (Everett B.Woodruff, 1998).

A boiler, or steam generator, is a closed vessel in which water, under pressure, is transformed into steam by the application of a suitable amount of heat. to the references (Michael C. McGoodwin, 2016) and (W.M. Rohsenow, J.P. Hartnett, Y.I. Cho, 1998) are perfect sources to understand all the thermodynamics concepts that are required in the present paper.

The first step before starting any procedure is to have a description of the physical system. In this case, a nonlinear dynamic model of the generic plant is obtained. The most well-known nonlinear dynamic control-oriented model for this kind of boilers is by Åström and Bell model. The "Drum- boiler dynamics" of Åström and Bell (K.J. Åström, R.D. Bell, 2000) is a fundamental corner stone almost of any studies in this field since it is a perfect combination fidelity and simplicity.

The goal of this work is to develop a control strategy to tackle the moderately complex non-linear model that captures the key dynamical properties of the steam drum boiler over a wide operating range (K.J. Åström, R.D. Bell, 2000).

In order to improve plant performance and flexibility as well as to reduce commissioning times, nowadays, the trend is to exploit a reliable simulation to design advanced control systems.
It may seem surprising that a traditional controller as simple as PID controller can behave well enough, at least so far (K.J Astrom, Tore Hagglund, 1995). However, the market needs impose to improve performance ever and ever.

As shown in (F.Morilla, march 2012), there is an extensive works ongoing with boiler pressure and level control systems. Mainly, they have been built up

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as combination of conventional single variable control loops and computation of variables that cannot be measured directly (Balchen & Mumme, 1988). Advanced control techniques have also been proposed to improve the performance of the control system in comparison of a decentralized one (Tan, et al., 2004). More complex and robust methodologies such as LQG/LTR, H∞-control, predictive control, and fuzzy control, have been also applied to improve boiler performance (Tan, et al., 2005) in specific cases. Based on (Sanjoy Kumar Chakraborty, Nilotpal Manna and Surodh Dey, April 2014) the importance of three-elements boiler drum level control has been presented. From (Keyur Solanki, Jalpa Shah, Nishith Bhatt, 2014), we can also prove previous assumption on the level control scheme based on the 3-element controller.

In this paper an adaptive control strategy will be proposed to cope with nonlinearity of the boiler while regulating its process characteristics on the desired value. The whole procedure is done based on the following pillars. First, a mathematical description is provided through a nonlinear model for steam drum of a D-type water tube boiler with natural circulation. The model is derived from first principle modelling method and is based on physical principles and construction data. To validate the model, some real data from a specific boiler have been considered and used to tune the mdoel according to the classic grey-box approach. Second, to compensate the nonlinearities of the model, we divide the whole operating range into several smaller ranges where the process can be approximated by linear models. By using system identification techniques, it is possible to obtain many black-box models of the system, linearized around various working conditions. Each black-box model is only valid closed to its corresponding operating point. Then, a specific controller (a PID for compliance with the market) is designed for each working point. Finally, two adaptive techniques have been conveived and tested: a gain-scheduling one and an adaptive one based on interpolation approaches.

2 MODEL DESCRIPTION

2.1 D-type Water Tube Boiler

As a general working principles of D-type water tube boiler, tubes are used to convey water and steam through the boiler. The combustion gases flow pass the outside surfaces of the tubes. The simplified sketch of D-type water tube boiler configuration is shown in Figure1. This boiler consists of a series of tubes and two drums (upper and lower ones). Drums distribute water to the tubes and these water tubes connect the drums and form a wall around the combustion area, where the heat is generated. Water is transferred into the upper drum through a feed water inlet line. The water tubes which is called 'down comers' and the lower drum is filled completely with water and the upper drum is only filled with water to a certain level to provide space for the steam. The upper drum is called 'steam drum'. As fuel is burned in combustion area, heat is transferred to the adjacent tubes named 'risers'. Water circulate from steam drum through down comers and into the lower drum.

Lower drum is referred to as the 'mud drum'. From mud drum, water is distributed to the risers surrounding the combustion area. Water in risers is heated and steam-water mixture is produced and enters the steam drum. Steam is separated from water and goes to the steam outlet and eventually into the plant.

Steam drum has a very complex mechanism and it has a tricky behaviour. In this project, the main focus is on the designing the suitable control system for steam drum.

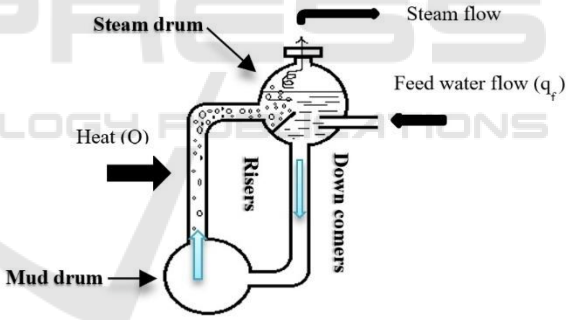

Figure 1: D-type water tube boiler.

2.2 Nonlinear Dynamic Model of Steam Drum Boiler

A key property of boilers is that there is a very efficient heat transfer due to boiling and condensation. All parts of the system which are in contact with the saturated water-steam mixture will be considered in thermal equilibrium. Energy stored in steam and water is released or absorbed very rapidly when the pressure changes. This mechanism is the key for understanding boiler dynamics. The rapid release of energy ensures that different parts of the boiler change their temperature in the same way (K.J. Åström, R.D. Bell, 2000).

The model is derived from first principles of thermodynamics laws, and is characterized by a few physical parameters (K.J. Åström, R.D. Bell, 2000). Variables subject to conservation laws are (Cooper, 2005): mass, energy and momentum.

Balance equations are then created by defining a boundary around the process.

Note that level, temperature and process variables other than those listed above are not conserved.

2.3 Mathematical Model

This section follows the Åström and Bell model which is a nonlinear dynamic model for steam drum of D-type water tube boiler with natural circulation.

By considering the schematic view of boiler in Figure 1, let the main inputs be heat flow to the system (Q), feed water mass flow rate (q_f) and steam mass flow rate (q_s). Moreover, let the outputs be drum pressure (P) and level variation (L).

Since first-principles dynamic model results from the conservation equations, the balance equations are:

- The global mass balance:

$$\frac{d}{dt}[\rho_s V_{st} + \rho_w V_{wt}] = q_f - q_s$$

- The global energy balance:

$$\frac{d}{dt}[\rho_s u_s V_{st} + \rho_w u_w V_{wt} + m_t C_p t_m] = Q + q_f h_f - q_s h_s$$

By substituting the internal energy 'u' with $u = h - \frac{P}{\rho}$, the global energy balance can be written as:

$$\frac{d}{dt}[\rho_s h_s V_{st} + \rho_w h_w V_{wt} - P V_t + m_t C_p t_m] = Q + q_f h_f - q_s h_s$$

This equation represents the energy flow to the system from fuel and feedwater and the energy flow from the system via steam.

The total volume of the drum, down comers and risers which is a constant value is:

$$V_t = V_{st} + V_{wt}$$

By combining these equations with saturated steam tables yields a simple boiler model which describe only the behaviour of the drum pressure P to manipulations of the inputs heat, feed water flow rate and steam flow rate. But it cannot capture the behaviour of the drum level. Eventually a model must be obtained not only describe the behaver of the pressure in the drum but also describe the distribution of steam and water in the system.

The final form of model in format of state equations are as below:

$$\begin{cases} e_{11}\frac{dV_{wt}}{dt} + e_{12}\frac{dP}{dt} = q_f - q_s \\ e_{21}\frac{dV_{wt}}{dt} + e_{22}\frac{dP}{dt} = Q + q_f h_f - q_s h_s \\ e_{32}\frac{dP}{dt} + e_{33}\frac{d\alpha_r}{dt} = Q - \alpha_r h_c q_{dc} \\ e_{42}\frac{dP}{dt} + e_{43}\frac{d\alpha_r}{dt} + e_{44}\frac{dV_{sd}}{dt} = \frac{\rho_s}{T_d}(V_{sd}^{\circ} - V_{sd}) \\ \qquad + \frac{h_f - h_w}{h_c} q_f \end{cases}$$

Where the coefficients e_{ij} are as follows:

$$\begin{cases} e_{11} = \rho_w - \rho_s \\ e_{12} = V_{st}\frac{\partial \rho_s}{\partial P} + V_{wt}\frac{\partial \rho_w}{\partial P} \\ e_{21} = \rho_w h_w - \rho_s h_s \\ e_{22} = V_{st}\left(h_s\frac{\partial \rho_s}{\partial P} + \rho_s\frac{\partial h_s}{\partial P}\right) + V_{wt}\left(h_w\frac{\partial \rho_w}{\partial P} + \rho_w\frac{\partial h_w}{\partial P}\right) \\ \qquad - V_t + m_t C_P\frac{\partial t_s}{\partial P} \\ e_{32} = \left(\rho_w\frac{\partial h_w}{\partial P} - \alpha_r h_c\frac{\partial \rho_w}{\partial P}\right)(1 - \bar{\alpha}_v)V_r + \\ \qquad \left(h_c(1 - \alpha_r)\frac{\partial \rho_s}{\partial P} + \rho_s\frac{\partial h_s}{\partial P}\right) \\ \qquad \bar{\alpha}_r V_r + (\rho_s + \alpha_r(\rho_w - \rho_s))h_c V_r\frac{\partial \bar{\alpha}_v}{\partial P} - V_r + m_r C_p\frac{\partial t_s}{\partial P} \\ e_{33} = ((1 - \alpha_r)\rho_s + \alpha_r\rho_w)h_c V_r\frac{\partial \bar{\alpha}_v}{\partial \alpha_r} \\ e_{42} = V_{sd}\frac{\partial \rho_s}{\partial P} + \frac{1}{h_c}\begin{pmatrix} \rho_s V_{sd}\frac{\partial h_s}{\partial P} + \rho_w V_{wd}\frac{\partial h_w}{\partial P} - (V_{sd} + V_{wd}) \\ + m_d C_p\frac{\partial t_s}{\partial P} \end{pmatrix} \\ \qquad + \alpha_r(1 + \beta)V_r\left(\bar{\alpha}_v\frac{\partial \rho_s}{\partial P} + (1 - \bar{\alpha}_v)\frac{\partial \rho_w}{\partial P} + (\rho_s - \rho_w)\frac{\partial \bar{\alpha}_v}{\partial P}\right) \\ e_{43} = \alpha_r(1 + \beta)V_r(\rho_s - \rho_w)\frac{\partial \bar{\alpha}_v}{\partial \alpha_r} \\ e_{44} = \rho_s \end{cases}$$

In addition, steam table are required to evaluate h_s, h_w, ρ_s, ρ_w, t_s, and partial derivatives with respect to pressure at saturated pressure P.

The Table 1 and Table 3 summarize all the parameters and their definitions.

Table 1: Parameters definition of the boiler.

Parameters	Definition
q_s	Steam mass flow rate
q_f	Feed water mass flow rate
q_{sd}	Steam flow rate through the liquid surface in drum
q_{dc}	Down comer flow rate
q_{cd}	Condensation flow rate
q_{ct}	Total condensation flow rate
Q	Heat flow rate to risers (heat supplied to the tubes)
V_t	Total volume
V_{st}	Total volume of steam
V_{wt}	Total volume of water

Table 2: Parameters definition of the boiler (cont.).

Parameters	Definition
V_{wt}	Total volume of water
V_{sd}	Volume of steam under the liquid level in the drum
V_{wd}	Volume of water under the liquid level in the drum
V_{sd}°	Volume of steam in drum in hypothetical situation when there is no condensation of steam in drum
P	Pressure
m_t	Total mass of drum and metal tubes

Model assumptions are:

- The two phases of the water inside the system are in saturated thermodynamics state everywhere.
- There is an instantaneous and uniform thermal equilibrium between water and metal everywhere.
- Steady state metal temperature is close to saturation temperature and the temperature differences are small dynamically.
- In this model water has natural circulation.

3 GAIN SCHEDULING CONTROL STRATEGY

Gain scheduling is a technique that deals with nonlinear processes, process with time variations or situations where the requirements on the control change with the operating conditions. To use this technique, it is necessary to find measurable variables, called scheduling variables, that are well correlated with changes in process dynamics.

This method is one possible scenario to design a control system for drum boiler over the whole operating conditions. A scheduling variable is first determined. Its range is quantitated into a number of discrete operating conditions.

The controller parameters are then determined by automatic tuning when the system is running in one operating condition. For each working point, as it has been shown in Figure 2, there are 3 PID controllers, one for pressure loop on which the pressure is control by heat and two for the two loops cascade control for controlling the level variations.

Therefore, for each working points the PID controller have been designed with the help of corresponding estimated linearized models based on the black box identification methods.

Table 3: Parameters definition of the boiler.

Parameters	Definition
ρ_w	Specific density of water
ρ_s	Specific density of steam
t	Temperature
h_c	Condensation enthalpy
h_s	Specific enthalpy of saturated steam
h_w	Specific enthalpy of saturated water
u	Internal energy
C_P	Specific heat of metal
L	Drum level
L_w	Level variation caused by changes of the amount of water in the drum
L_s	Level variation caused by steam in drum
L_r	Length of the risers
L_{dc}	Length of the down comers
A	Cross section of tube
A_d	Wet surface
α_m	Steam-mass fraction
α_v	Steam-volume fraction
α_r	Steam quality at riser outlet
ζ	Normalized length coordinate along the risers
T_d	Residence time of the steam in drum

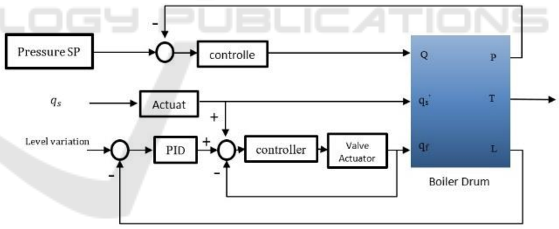

Figure 2: Drum-Boiler control scheme.

3.1 Model Linearization

In this section, eight different working points have been considered which result in eight various models from identification and linearization methods. Since in a nonlinear system there are so many option for choosing the intended points, for the predefined system the equilibrium points are consider at different value of heat Q and pressure P corresponding to their nominal values.

The model has been validated in various equilibrium points presented in Table 4.

Table 4: Various equilibrium points for Drum-Boiler.

Working points conditions			$q_s = q_f$ (kg/sec)	T_f (°C)	P_f (bar)	P_0 (bar)	T_0 (°C)
1st	Q: 10% of nominal	P: 10%	1.4224	105	44.4	44.4*10%	1.4741e+02
2nd		P: 40%	1.3905	105	44.4	44.4*40%	2.0645e+02
3rd		P: 60%	1.3863	105	44.4	44.4*60%	2.2736e+02
4th		P: 100%	1.3888	105	44.4	44.4*100%	2.5662e+02
5th	Q: 20% of nominal	P: 10%	2.8449	105	44.4	44.4*10%	1.4741e+02
6th		P: 40%	2.7810	105	44.4	44.4*40%	2.0645e+02
7th		P: 60%	2.7727	105	44.4	44.4*60%	2.2736e+02
8th		P: 100%	2.7777	105	44.4	44.4*100%	2.5662e+02

According to the strong interactions between the inputs and outputs of the steam-drum boiler model (Figure 2), a linear MIMO system should be estimated in each working point.

In this paper, the first 4 working points are just considered to implement the control strategies. In this case, the linearized models for the first 4 working points can be summarized in the Table 5, Table 6, Table 7 and Table 8:

Table 5: Linearized MIMO system in the 1st working point.

	Heat (Q)	Feed water flow rate (q_f)	Steam flow rate (q_s)
Pressure(P)	$\frac{9.192e-06(s+1)}{s+1.324e-5}$	$\frac{-6.485e-08(s+1)}{s+1.751e-05}$	$\frac{-8.009e-07(s+1)}{s+1.781e05}$
Level(L)	$\frac{0.6276\,s+1.561}{s^2+1.345\,s+0.3712}$	$\frac{0.3692\,s\hat{}2+0.9056\,s+0.6915}{s^2+1.344\,s+0.3663}$	$\frac{0.2807\,s+0.6983}{s^2+1.346\,s+0.375}$

Table 6: Linearized MIMO system in the 2nd working point.

	Heat (Q)	Feed water flow rate (q_f)	Steam flow rate (q_s)
Pressure(P)	$\frac{2.563e-06(s+1)}{s+6.045e-6}$	$\frac{-4.603e-07(s+1)}{s+7.08e-06}$	$\frac{-2.155e-06(s+1)}{s+7.512e-06}$
Level(L)	$\frac{-1.471e-07\,s^2-7.368e-08\,s+8.961e-07}{s^3+0.9954s^2+0.1519\,s+1.038e-06}$	$\frac{-2.009e-06\,s^2-1.008e-06\,s+1.224e-05}{s^3+0.9966\,s^2+0.1532\,s+0.0002504}$	$\frac{-5.861e-07\,s^2+1.492e-06\,s-1.378e-06}{s^3+0.9956\,s^2+0.152\,s+3.026e-05}$

Table 7: Linearized MIMO system in the 3rd working point.

	Heat (Q)	Feed water flow rate (q_f)	Steam flow rate (q_s)
Pressure(P)	$\frac{3.62e-08(s+1)}{s+2.091e-06}$	$\frac{-7.756e-11(s+1)}{s+2.112e-06}$	$\frac{-2.85e-10\,(s+1)}{s+2.408e-06s+2.112e-06}$
Level(L)	$\frac{0.001629}{s+0.05304}$	$\frac{6.707e-05\,s-0.0001186}{s^2+0.7322\,s+0.1005}$	$\frac{-4.174e-05\,s-9.423e-05}{s\hat{}2+0.7322\,s+0.1005}$

Table 8: Linearized MIMO system in the 4th working point.

	Heat (Q)	Feed water flow rate (q_f)	Steam flow rate (q_s)
Pressure(P)	$\frac{-5.285e-11\,s-1.057e-10}{s^2+5.679e-06\,s+1.842e-11}$	$\frac{1.294e-11\,s-4.754e-11}{s^2+3.726e-06\,s+8.738e-12}$	$\frac{-6.168e-06\,s-1.169e-05}{s+2.09e-06}$
Level(L)	$\frac{-4.811e-06\,s-1.018e-05}{s\hat{}2+0.3287\,s+7.946e-07}$	$\frac{8.398e-05\,s-0.0001499}{s^2+0.6781\,s+0.08432}$	$\frac{6.605e-05\,s-0.0001179}{s^2+0.678\,s+0.08428}$

3.2 Gain-Scheduling Implementation for Warm-up Condition

According to the control scheme given in Figure 2, three PID controllers for each working point are needed as following:

- Pressure loop PID controller
- Level loop cascade control scheme (including 2 PID controllers)

To sum up, by now four sets of PID controllers have been designed. A very initial condition has been defined for the real existing drum boiler used as a test case, at which the boiler start to work from pressure equal to 4 bar to its nominal value which is 44.4 bar. The value of initial condition is arbitrary chosen and it is better not to be close to the cold start up condition, i.e. 0 bar for long time.

The first aim is to start from predefined initial condition and reach the first working point as the first set point. The first operating condition is considered as the initial condition of the next stage to reach the next operating work till the last operating point which corresponds to the nominal pressure.

According to the gain scheduling approach, the PID can be tuned as follows:

$$PID(s) = \frac{K}{\mu_G \tau_G} \frac{(1+s\tau_G)\left(1+s\frac{\tau_G}{N}\right)}{s(1+s\tau_p)}$$

where K and N can be chosen to act on the velocity of the control loop and τ_p is a high-frequency pole for the controller feasibility. In Table 9: Gain-scheduled controller parameters tuned parameters in different working points have been shown.

Table 9: Gain-scheduled controller parameters.

	Working point	PID controller				
		Control loop	P	I	D	N
Q = 10 % of nominal value	1st	Pressure	12946390.8562979	57364.4973633716	185140084.044049	0.105804031715037
		Feed-water	150	2	1	1000
		Steam	1.69440844087723	0.204639135034243	1.11926329741383	0.306413524971208
	2nd	Pressure	64477178.0537786	1120035.71042669	71676365.9941274	0.353279018426477
		Feed-water	150	2	1	1000
		Steam	1.3375803137951	0.267355246643925	0	0.378094165182863
	3rd	Pressure	43561754.0548752	989985.477749903	30393072.3674514	2.54198624295923
		Feed-water	200	2	10	1000
		Steam	16.755443714114	7.93246992931621	0.762153879123082	1.78101552647807
	4th	Pressure	4194414.62760401	31512.3541165832	0	100
		Feed-water	100	2	1	100
		Steam	17.212676128039	8.33953004731139	0	100

By applying the gain scheduling method and set point scheduling, it can be demonstrated that whether each set of controllers can work properly during their operating conditions and automatically switch to the next operating point when the pressure reaches the set point value. Figure 3 shows the general definition of this method.

As it can be seen in Figure 3, each set of controllers works very well at their corresponding working point. It means that the set point following can be satisfied for the boiler model in nominal pressure by implementing the gain-scheduled

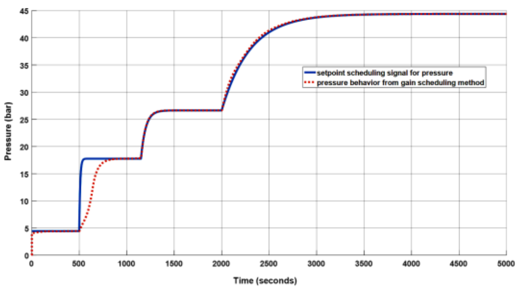

Figure 3: Drum pressure in different working points based on gain scheduled controller.

controller. This method is compared with a single set of PIDs for the same set point. Figure 4 and Figure 5 illustrate this comparison for pressure and level control loops.

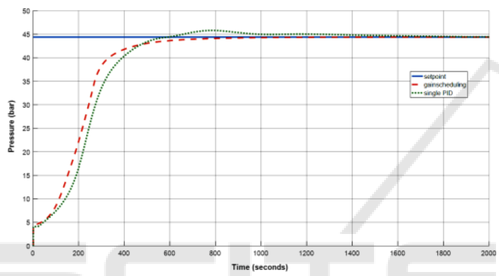

Figure 4: Gain-scheduled controller on drum pressure loop (desired value: 44.4bar).

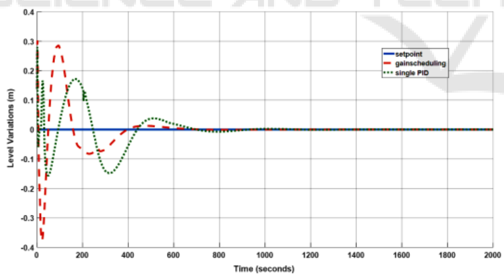

Figure 5: Gain-scheduled controller on drum variation level loop (desired value: zero variation).

4 SELF-TUNING CONTROL SCHEME

As it has been show in section 3, gain-scheduled controller has better time domain characteristics, i.e. faster, no overshoot and smother response. Although it seems that gain-scheduled controller performs numerically in a proper way, it will confront with some limitation in practical application.

On the one hand, gain-scheduled method requires a large effort to be implemented but when it combined with auto-tuning, it will be very easy to use.
On the other hand, it will have adverse effects on the industrial fields due to switching behaviour among all controllers.

In this section, some interpolation approaches will be used to design an adaptive function for each control loop, i.e. pressure and level control loops.

In this case, the output of the system will be filtered by a discrete filter to prepare an average value rather than single one signal for the adaptive function. After that the PID controllers will be retuned based on the adaptive functions. The proposed adaptive strategy is sketched in Figure 6 where E_{max} is the maximum possible input for the boiler, P_{max} maximum output pressure, G(s) is the boiler dynamic model and $\widetilde{R}(s)$ is normalized controller.

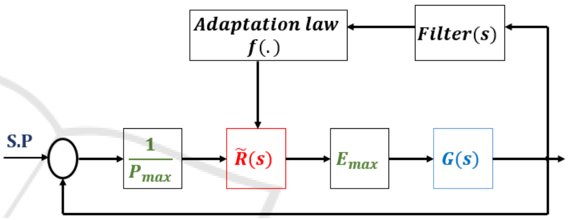

Figure 6: Self-tuning control scheme.

Adaptive functions are designed based on the linear interpolation of the given PID controllers in the gain-scheduled method. So, the PID parameters will be updated based on the following adaptive functions:

A. Pressure control loop

$$\text{Proportional gain} \begin{cases} f_1(p) = 5.205 * p - 5.692 \\ f_2(p) = -3.169 * p + 143 \\ f_3(p) = -2.982 * p + 138.1 \end{cases}$$

$$\text{Integral gain} \begin{cases} f_1(p) = 0.1073 * p - 0.3994 \\ f_2(p) = -0.0197 * p + 1.857 \\ f_3(p) = -0.07261 * p + 3.266 \end{cases}$$

$$\text{Derivative gain} \begin{cases} f_1(p) = -11.46 * p + 300 \\ f_2(p) = -6.255 * p + 207.5 \\ f_3(p) = -2.303 * p + 102.2 \end{cases}$$

B. Level control loop – Outer loop

$$\text{Proportional gain} \begin{cases} f_1(p) = 150 \\ f_2(p) = 5.631 * p + 50 \\ f_3(p) = -11.26 * p + 400 \end{cases}$$

Integral gain: constant value equal to 2.

$$\text{Derivative gain} \begin{cases} f_1(p) = 1 \\ f_2(p) = 1.014 * p - 17 \\ f_3(p) = -1.014 * p + 28 \end{cases}$$

C. Level control loop – Inner loop

$$\text{Proportional gain} \begin{cases} f_1(p) = -0.02679 * p + 1.813 \\ f_2(p) = 1.736 * p - 29.5 \\ f_3(p) = -0.02575 * p + 16.07 \end{cases}$$

$$\text{Integral gain} \begin{cases} f_1(p) = 0.004708 * p + 0.1837 \\ f_2(p) = 0.8632 * p + 15.06 \\ f_3(p) = 0.02292 * p + 7.322 \end{cases}$$

$$\text{Derivative gain} \begin{cases} f_1(p) = -0.08403 * p + 1.492 \\ f_2(p) = 0.08583 * p - 1.524 \\ f_3(p) = -0.04291 * p + 1.905 \end{cases}$$

The PID coefficients profile have been shown in Figure 7 and Figure 8. The updated PID is used in a drum boiler initialized by 4 bar as the initial pressure and 20 seconds as the filter time constant.

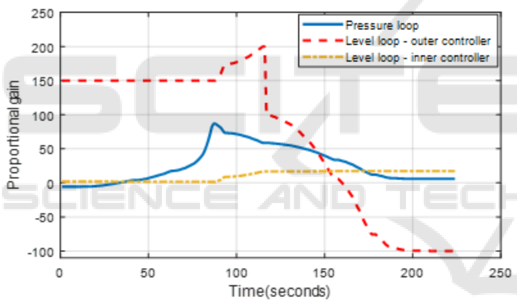

Figure 7: The PID coefficients profiles in adaptive control.

In this paper, a steam drum boiler endowed with a gain scheduling control and an adaptive control scheme has been considered for both control loops, i.e. pressure and level control loops. As it has been shown in Figure 9 the gain scheduled controller is a little bit faster, but as it mentioned it has adverse effects in the practical application. Simplicity, safety and accuracy are the most important advantages of the self-tuning approach.

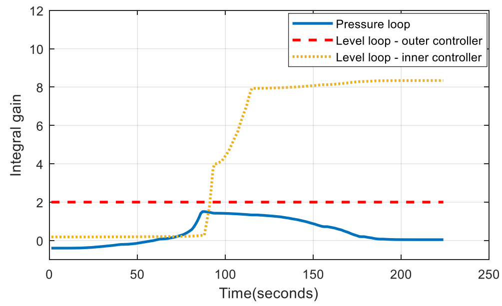

Figure 8: The PID coefficients profiles in adaptive control.

Although it is a bit slower than gain-scheduled controller, it uses one adaptive PID controller rather than a number of controllers.

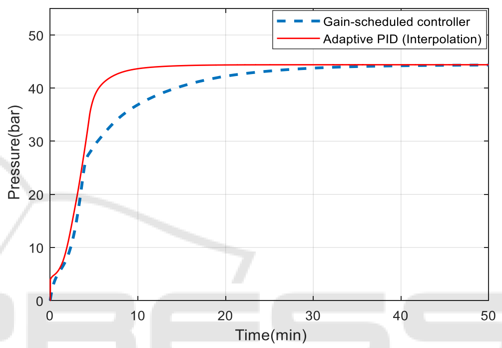

Figure 9: Comparison between self-tuning controller and gain-scheduled method.

Time constant of the filter is a crucial property of the adaptive control scheme for boiler pressure control. In Figure 10 the effects of different filter time constant are evaluated.

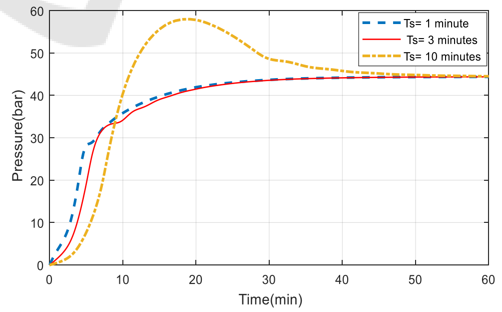

Figure 10: Effect of filter time constant on pressure loop.

5 CONCLUSIONS

The aim of the paper is modeling and control of medium-size industrial boilers (D-type water tube boiler). Following the “Åström and Bell” model, a complex nonlinear dynamic model for natural circulation of drum boilers has been derived. A real drum boiler has been considered as a test case and the model validated against the real case.

A single PID cannot cope easily with the system nonlinear behavior.I It is more reasonable to extend the number of working points and using the proper controller for each linearized region. Each working point has a set of PID controllers; one for pressure loop and the other two for the two loops of the cascade control based on the three elements level control. Among all eight working points computed, the first 4 have been chosen to represent the transient behavior of the pressure till its nominal value.

Gain scheduling approach has been applied to select the proper controller for each linearized model in a discretized region. At the end an adaptive control structure endowed by a linear interpolation function has been considered to ease the control effort, decrease the number of controllers and alleviate the adverse effects of switching phenomena due to gain scheduling methods. As it has been shown in the simulation results, the implementation results had satisfactory results.

Future directions include developing a better tuning of the adapting technique (with more points and finer interpolations) as well as integrating a more complex decision rule. Also, robust control techniques will be investigated.

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