Reduced Energy Cost through the Furnace Pressure Control in Power Plants

Vojislav Ž. Filipović
University of Kragujevac
82 PUBLICATIONS **358** CITATIONS

Novak N. Nedic
University of Kragujevac
60 PUBLICATIONS **750** CITATIONS

Reduced Energy Cost through the Furnace Pressure Control in Power Plants

Vojislav Ž. Filipović[a]*, Novak N. Nedić*[b] *and Saša Lj. Prodanović*[c]

[a] *University of Kragujevac, Faculty of Mechanical Engineering Kraljevo, Kraljevo, Serbia, v.filipovic@open.telekom.rs ,*
[b] *University of Kragujevac, Faculty of Mechanical Engineering Kraljevo, Kraljevo, Serbia, nedic.n@mfkv.kg.ac.rs ,*
[c] *University of East Sarajevo, Faculty of Mechanical Engineering, East Sarajevo, Bosnia and Herzegovina, elsing123@yahoo.com,* ***CA***

Abstract:

Maintaining pressure in the boiler's furnace is one of the key requirements for proper combustion in steam boilers in thermal power plants. This paper proposes a control strategy that eliminates flap in the channel for the output gases. This is achieved by applying the frequency regulator for asynchronous motor speed control. Reference value for the frequency regulator is obtained through the PI controller. Special attention is given to tuning of PI controller. Well-tuned PI controller with the use of frequency regulator provides significant energy savings, because asynchronous motor for ventilator of steam boiler in thermal power plants has a large power. Modification of relay feedback experiment has supported λ-tuning of controller whose two types (faster and robust) were tuned. This modification consists in:

a) Replacement of relay characteristic with saturation curve,

b) Fourth-order process identification with first-order process plus dead time.

The methodology is illustrated by simulations.

Keywords:

Energy saving, Combustion, Frequency regulator, PI controller, λ-tuning.

1. Introduction

Steam boiler, as well as the other components of power plant, performs energy transformation. Therefore, energy dissipation, during combustion process, is present here. This paper considers and suggests possibilities for energy saving by changing in strategy of furnace pressure control as part of boiler. That means replacing of damping control with strategy which is based on frequency regulators (variable-speed drives). Namely, furnace output gases are controlled by ventilators (fans) instead by flap (valve) in output channel. The aim of this paper is to build new control loop for furnace pressure using frequency regulators for asynchronous motor speed control, which drives ventilator.

In this control system, PI (proportional – integral) controller generates reference values for frequency regulator [1]. In order to explore an adequate tuning of PI controller, the method for process identification using relay feedback test was carried out using simulation. Saturation relay will be applied instead ideal relay because of its well known advantages [1]. Unlike previous research, fourth-order process was identified as true first-order process plus relative small dead time [2]. Afterward, method of λ-tuning gives parameters of PI controller, which is adequate for first-order process. Because of the possibility of different conditions during operation of the system, two types of PI controller (faster and robust) will be tuned [1]. Their quality will be explored after simulation of entire control loop for furnace pressure and analysing of process response. Essentially, this survey tends to exploit simulation as a tool for considering improvements of existing control system. Accordingly, researches in this paper are focused on reducing the energy consumption that is necessary for the operation of thermal power plant, which directly means increasing the amount of electricity for delivery to customers [3].

2. Model of system

Good combustion in furnace of steam boiler enables better parameters of steam and better utilization of coal and in that way greater efficiency and lower costs. It is being obtained by maintenance of the furnace pressure on reference value which is required for well combustion. Furnace pressure control is necessary for controlling of quantities of O_2 and CO during combustion process [4]. Mentioned pressure depends on air circulation through the furnace. There are four ventilators, one couple for input of air and the other for output of gases. Because of larger flow on outlet, furnace is under vacuum. It is shared in two parts: upper and lower. In following exposures two approaches of furnace pressure control will be presented.

2.1. Damping model for furnace pressure control

This model is very widespread in thermal power plants. It is based on valve (flap) for furnace output gases. Therefore, asynchronous motors for ventilators always work with full power during exploitation. That causes energy dissipation on valves, as its main drawback, because output flow of gases is being controlled only by flap rotating. Namely, valves perform a damping here. Knowledge of the constituent components of the control system and connection between them and than their behaviour equations have enabled the formation of a general block diagram of the said control system. Of course, as so often in the modelling, to simplify a constructed mathematical model assumptions have been introduced [5]. General block diagram for this strategy is shown in Fig. 1.

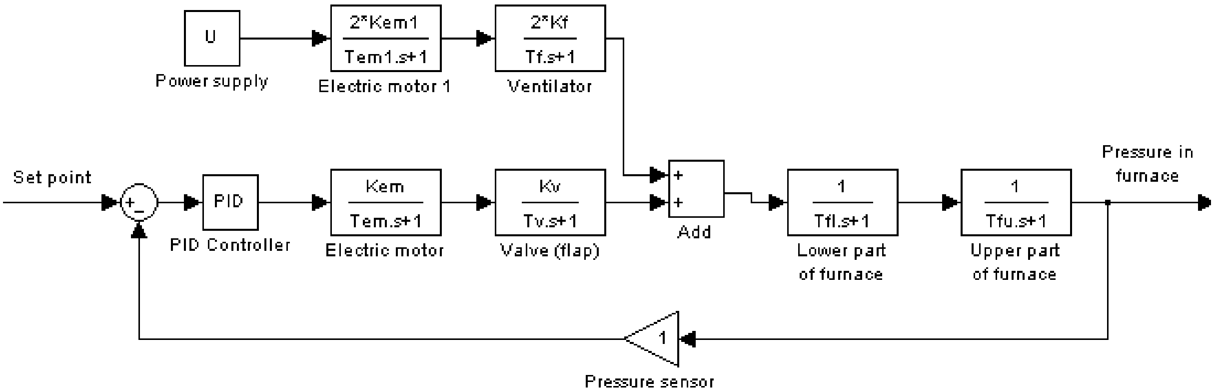


Fig. 1. General block diagram for damping control strategy [5]

2.2. Suggested model with frequency regulators

High power of asynchronous motors for ventilators leads to significant possibilities for energy saving by reducing their consumption. That might be enabled using frequency regulators for speed control of asynchronous motor. For example, in the thermal power plant Gacko (Bosnia and Herzegovina) both electric motors for ventilators in output channel of furnace have the same power P = 3,2 MW [6]. Configuration for application of this energy saving strategy is shown in Fig. 2, where dynamics of frequency regulators and pressure sensor haven't been considered because of small values of their gains and time constants. Hence those transfer functions have been assumed as 1.

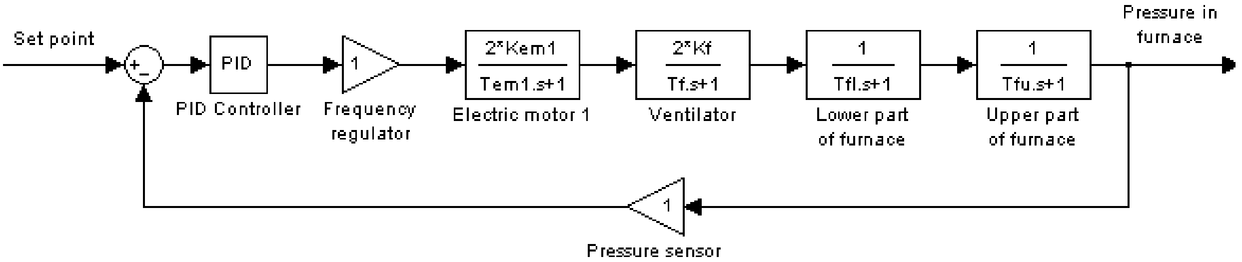


Fig. 2. General block diagram for strategy which is based on frequency regulators

In the both of strategies, gain and time constant of each component (i.e. transfer function) can be determined according physical laws or experimentally by recording their input and output signal.

The meanings of indexes of those components (blocks) have been given in nomenclature.

PI controller forms reference value for frequency regulator which is necessary for appropriate motor speed obtaining. Motor speed is being controlled by changing of power frequency. In order to keep constant torque, supply voltage should be controllable by frequency. In this way, frequency regulators provide power supply, which load (in our case ventilators) requires, and that is the key for energy saving [7]. Namely, torque for fan (ventilator) is:

$$M_f(t) = k_1 \omega^2(t) \tag{1}$$

power that should be obtained from the motor is:

$$P_f(t) = k_2 \omega^3(t) \tag{2}$$

where:

- $\omega(t)$ – angular speed,
- k_1 and k_2 – constants.

Now, reduction average speed of motor by 10% (which is usually feasible) leads to decrease in energy consumption by 27%, because it is calculated: $1 - (0{,}9)^3 \approx 1 - 0{,}73 = 0{,}27$.

This approach involves omission of valves, electric motors for its drive, and other components such as gearboxes and valve position sensors and thus increases savings.

In order to present general values of savings, here are calculated and shown in Table 1 possible savings in mentioned thermal power plant Gacko, i.e. in its electric motors for ventilators. In this calculation was taken into account that that thermal power plant operates up to 7000 hours per year, because of its regular maintenance and unexpected failures.

Table 1. Energy saving of electric motor with reduction of its average speed by 10%

	Daily		Annual	
	Consumption MWh	Energy saving MWh	Consumption MWh	Energy saving MWh
Electric motor for ventilator P=3,2x2=6,4 MW	153,6	41,5	44800	12096

Therefore, annual saving in the amount of 12,096 GWh is very significant and enables greater delivery of electricity to consumers.

In addition to energy saving frequency regulators allows: optimization of the process, "softer" functioning of driving and operating machines because of their smaller number of starts and stops, lower maintenance costs, longer equipment life and improved operating environment (for example, less fan noise). This theoretic approach, through these two control strategy, has been served as guideline for order assessment of process transfer function, which will be explained in next chapter.

3. Process identification

The knowledge transfer function of the process opens the opportunities of its analysis but also tuning of PI controller by various methods. It can be found on two ways: by modelling based on physical rules and using methodologies of identification.

Relay feedback test, which is often used for autotuning of PI controllers, here has been utilized for process identification [2]. In real conditions, this procedure involves introducing relay (as nonlinearity) into system in order to cause steady oscillations in its response and then obtain necessary information of the process. That method will be simulated in Matlab software.

For that purpose transfer function of process will be assumed. According general block diagram of system for furnace pressure control in Fig. 2, (where are four first-order components) this process can be taken as fourth-order process. Following exposure contains simulated and suggested methodology for process identification which is presented on example. Namely, in the absence of a real process model, transfer function is taken arbitrarily, as shown in Figs 4. and 7. In this case it is not disadvantage, but proof that the identification procedure which is carried out can be applied to any process.

Relay feedback test is based on saturation relay because of its advantages over ideal relay in estimating of ultimate gain and ultimate period.

In order to carry out process identification, i.e. obtain transfer function; following parameters should be determined [1]:

- *K* – steady state gain,
- *L* – dead time,
- T – time constant.

Then, this transfer function of first-order process is:

$$G(s) = \frac{K}{Ts+1} e^{-Ls} \qquad (3)$$

where: $K=\Delta y/\Delta u$ as it shown in Fig. 3.

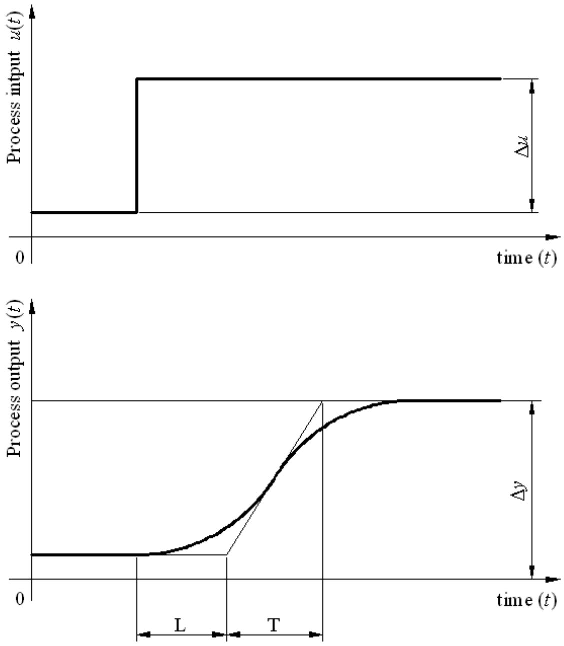


Fig. 3. Process input and output

Order of transfer function is obtained depending on category of system (based on integrated absolute error from frequency response), which is determined by *L/T* ratio and assumed order of the process. According partially demonstration in [2], in this example process will be presented with first-order process plus relative small dead time, as it shown in (3). In the following chapter its validation will be proved.

Now, mentioned parameters are given by [2] and follows:
first iteration to compute time constant, hence

$$T_1 = \frac{tg(\pi - L\omega_u)}{\omega_u} \tag{4}$$

afterwards, the second iteration follows

$$T = \frac{T_u/2}{\ln\left(2e^{L/T_1} - 1\right)} \tag{5}$$

and

$$K = \frac{a}{h\left(1 - e^{-L/T_1}\right)} \tag{6}$$

As previously stated, general procedure for identification will be presented on arbitrarily chosen process in folowing three steps:

First step

Performing relay feedback test using ideal relay to determine slope of saturation relay (*k*).

Fig. 4. shows configuration for carry out relay feedback test in Matlab software.

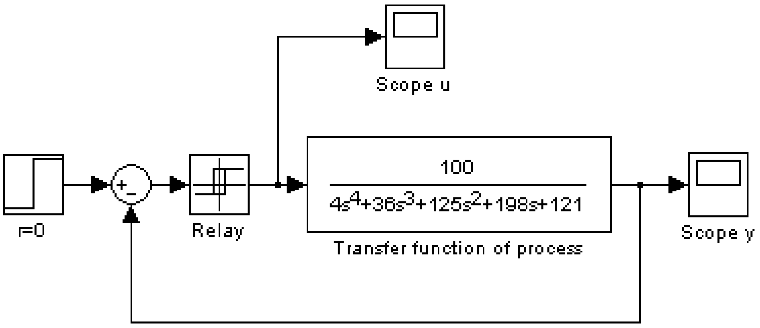


Fig. 4. Configuration for ideal relay feedback test [8]

At the beginning, height of ideal relay characteristic h = 0,03 bar has been set as Fig. 5 shows. Because $h = 0{,}1 \cdot SP$, where SP is set point of furnace pressure (in thermal power plant Gacko SP = 0,3 bar) [6]. This simulation gives relay output and relay feedback response, which is shown in Fig. 5 and 6, respectively.

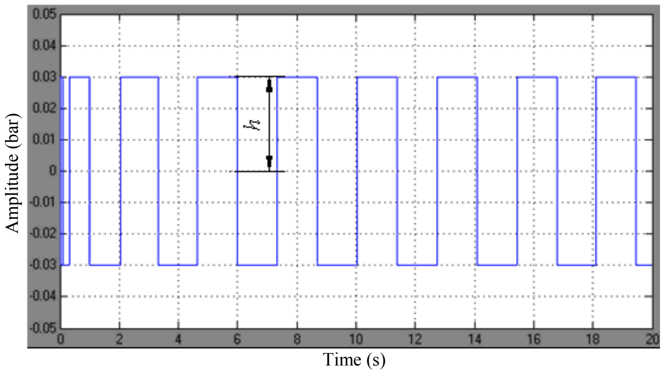
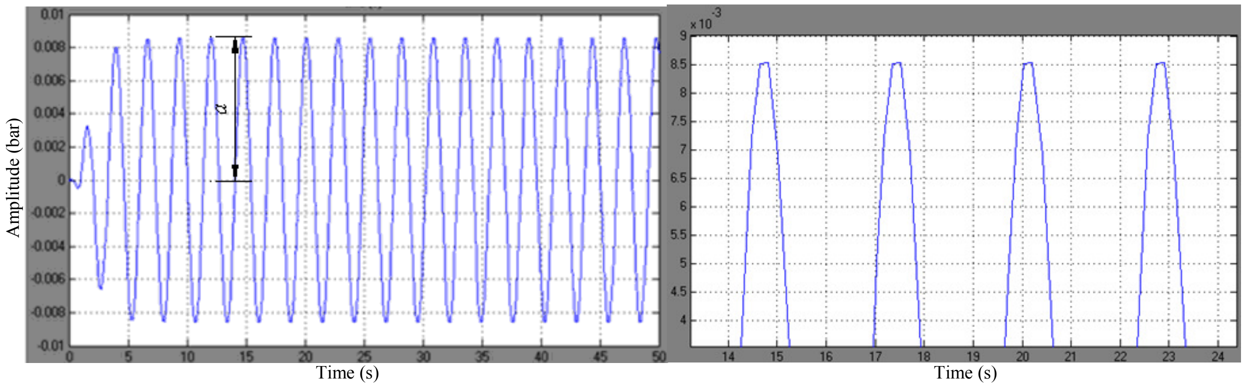


Fig. 5. Ideal relay output



(a) *(b)*

Fig. 6. Ideal relay feedback response: a) whole view, b) zoomed segment

Using diagrams in Fig. 6 amplitude of response has been determined: a = 0,0085 bar.

Now, ultimate gain is [1]:

$$K_u = 4h/\pi a = 4{,}5 \qquad (7)$$

where $K_u = k_{\min}$,

the slope of saturation relay is given by

$$k = 1{,}4 \cdot k_{\min} = 6{,}3 \qquad (8)$$

Second step

Carry out relay feedback test using saturation relay as it is presented in Fig. 7., and result is diagram shown in Fig. 8.

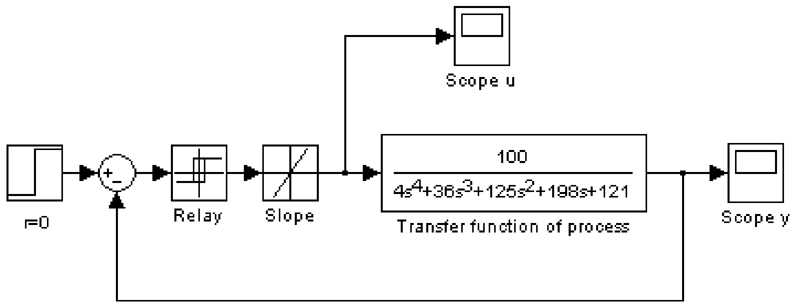
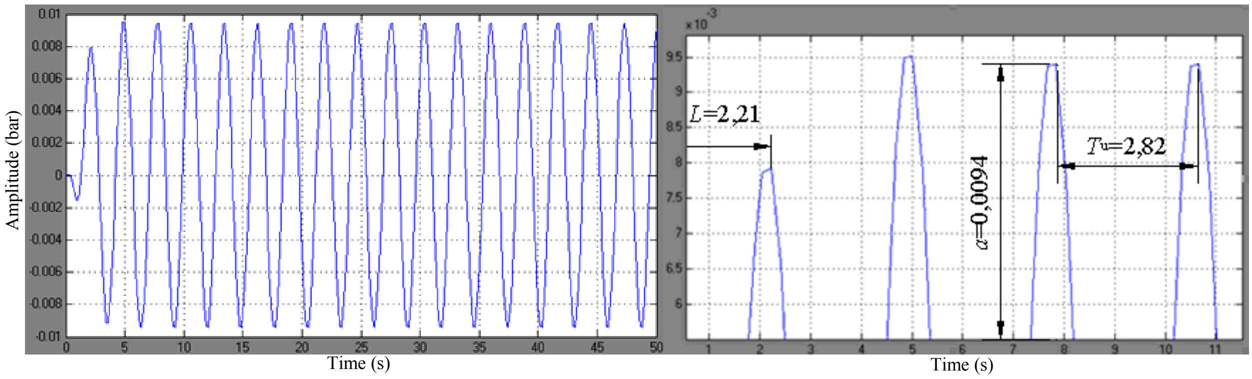


Fig. 7. Configuration for saturation relay feedback test



(a) *(b)*

Fig. 8. Saturation relay feedback response: a) whole view, b) zoomed segment

Amplitude of response a = 0,0094 bar, dead time L = 2,21 s and ultimate period T_u = 2,82 s have been determined from diagrams in Fig. 8. Than ultimate frequency can be calculated:

$$\omega_u = 2\pi / T_u = 0{,}71\pi \qquad (9)$$

Third step

Calculate necessary parameters to complete desired transfer function.

Afterward, using (4), (5) and (6) required parameters are obtained: T_1 = 2 s, T = 0,87 s and K = 0,47. Using (3) gives transfer function of process

$$G(s) = \frac{0{,}47}{0{,}87s + 1} e^{-2{,}21s}$$

It is very important to say that this process is described as true first-order process plus *relative small* dead time, because relay feedback response doesn't develop stationary oscillation in the first cycle (Fig. 8), unlike the previous practice whereby this process should be described by high-order process without dead time, because ratio L/T = 2,54 [2].

4. Tuning of PI controller

Since the process has been identified as first-order process, the best type of controller is PI.

λ-tuning method (Dalin) will be used for obtaining appropriate parameters of controller. This method is special case of method of pole design [1]. It is based on two assumptions:

1. integral time constant T_i is equal to time constant of the process T,
2. it is assumed that system's feedback contains one real pole s = –1 / λ where λ is desired time constant of that system.

Approximation of exponential article in (3) with two article of Taylor progression gives

$$G(s) = \frac{K(1 - Ls)}{Ts + 1} \qquad (10)$$

Using first assumption transfer function of PI controller is

$$G_c(s) = K_c\left(1 + \frac{1}{Ts}\right) \qquad (11)$$

Than characteristic equation of system derived with (10) and (11) is

$$1 + G(s)G_c(s) = 0 \qquad (12)$$

Based on mentioned assumptions and (10), (11) and (12) parameters of PI controller are obtained as follows

$$K_c = \frac{1}{K}\frac{T}{L + \lambda} \qquad (13)$$

$$T_\mathrm{i} = T \qquad (14)$$

According this method, heuristic rules are being used for determining of λ:

- λ = T for faster controller,
- λ = $3T$ for robust controller.

Afterward, parameters of PI controller for considered process are calculated:

- K_c = 0,6 and T_i = 0,69 for faster controller,

- $K_c = 0{,}38$ and $T_\mathrm{i} = 0{,}44$ for robust controller.

How tuned controllers operate within the system was tested by simulating the entire control system. Configuration in Fig. 9 performs mentioned simulation and required responses are given in Fig. 10.

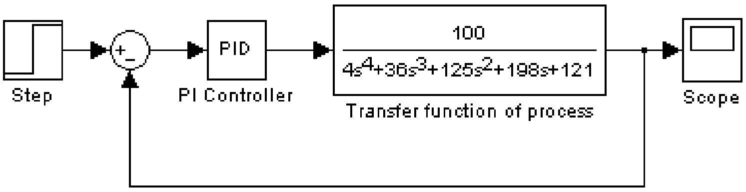
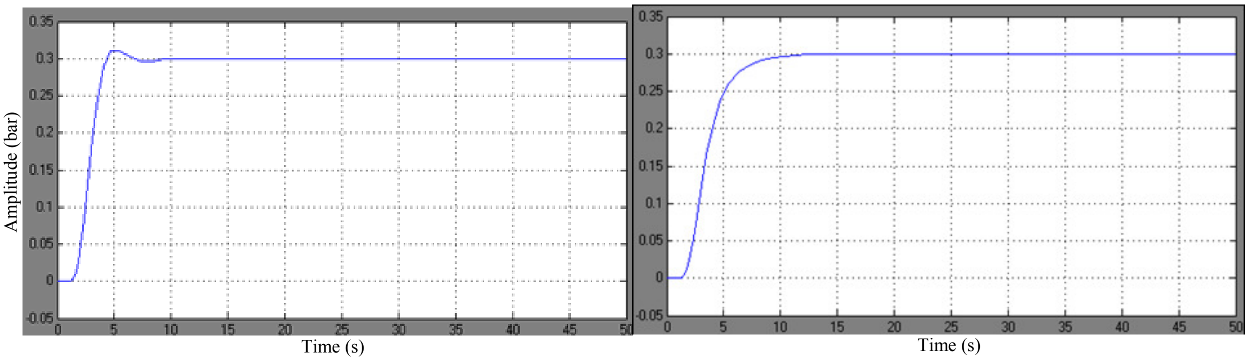


Fig. 9. Configuration for simulation of entire control system



(a) *(b)*

Fig. 10. Response of control system: a) with faster PI controller, b) with robust PI controller

These two responses directly reflect the names of controllers which causes them. Namely, response in Fig. 10.*a)* has shorter rise time and dead time as well as less than 10% overshoot, while other response is without overshoot and has monotonous rise what are the characteristics of its robustness. Responses have appropriate shape, i.e. both kind of PI controller are good, but their application depends on the operating conditions in which the system supposed to work.

Finally, presented responses justify applied identification process (i.e. assumed first-order process) and λ-tuning method for PI controller.

5. Conclusions

Control strategy which is based on frequency regulators ensures energy saving in two ways. First, through the total speed control of asynchronous motor and second, because enabling appropriate functioning conditions. That has been proved on furnace pressure control in thermal power plant, where was suggested replacing damping control method for output gases flow with strategy which involves variable speed drives for ventilator’s speed control.

The main contribution of this paper is proposing of procedure for process identification and λ-tuning of PI controller. In this research emphasis was placed on the use of exact method of tuning that is based on the estimated characteristics of the process. That procedure enables such control loops which can provides good behaviour of process and in that way make possible energy saving strategy. One of possibilities how to use simulations as tool for overcoming lack of laboratory equipment and real systems were proposed.

Nomenclature

a	amplitude,
G(s)	transfer function,

h	height of ideal relay characteristic,
K	steady state gain,
k	slope of saturation relay,
L	dead time, s
P	power, W
s	complex variable,
T	time constant, h
t	time, s
U	voltage, V

Greek symbols

Δ	change of signal,
λ	desired time constant, s
ω	angular speed, s^{-1}

Subscripts and superscripts

c	controller,
em	electric motor,
f	fan (ventilator),
fl	lower part of furnace,
fu	upper part of furnace,
i	integral,
u	input and ultimate,
v	valve,
y	output.

References

[1] Filipović VŽ, Nedić NN. PID Controllers. Kraljevo: University of Kragujevac, Faculty of Mechanical Engineering; 2008. (in Serbian).

[2] Yu, CC. Autotuning of PID controllers. Taipei, Taiwan: National Taiwan University, Springer; 2006.

[3] Prodanović S. Analysis and improvement of control system of condensate level in condenser of turbine in thermal power plant Gacko (master thesis). Kraljevo, Serbia: University of Kragujevac; 2009. (in Serbian).

[4] Buljubašić I. Modelling of processes in steam boilers as a part of performance monitoring. TTEM Journal 2006;1(2):34 – 39.

[5] Komatsu T. Instrumentation for boiler plant. Fuji Denki Review;9(6):164 – 168.

[6] Technical documentation of the control system of condensate level in condenser of turbine and of the entire thermal power plant Gacko.

[7] Filipović V, Nedić N, Pršić D, Dubonjić LJ. Energy saving with variable speed drives. Proceedings of the VI International Triennial Conference, Heavy Machinery – HM 2008: Kraljevo, Mataruška banja, pp. A1 – A6.

[8] Prodanović SLJ, Nedić NN, Filipović VŽ. Improved Auto-tuning PID Controller of Level in Condenser of Turbine in Thermal Power Plant Using Saturation-relay Feedback. Proceedings of the X Triennial International SAUM Conference on Systems, Automatic Control and Measurement, Niš, Serbia, 2010.