Three term controller tuning

1. Introduction

Tuning a three term controller means selecting the settings of the proportional band (or gain), reset time and derivative time to give acceptable performance. Because process plant dynamics are rarely well defined and can be quite non linear, there are no perfect settings. In practice controller tuning is normally a compromise between performance and robustness. Performance means that the control loop will respond quickly and accurately to reference value changes or disturbances and robustness means that the control loop will not be too oscillatory or even unstable should the pant dynamics change. Often the settings that give fastest performance also leave the control loop quite sensitive to changes in plant dynamics so a compromise must the achieved.

One might think that we can tune a controller by starting with simple proportional control and adjusting the gain to give acceptable overshoot. Then we can introduce integral action to remove the offset, again adjusting the reset time until the response starts to become slightly more oscillatory. Finally, derivative can gradually be added to reduce the overshoot to an acceptable level. Several problems exist with this method. Each trial requires a closed-loop step response test allowing the plant to settle and then bringing it back to the starting point ready for the next trial. If the plant has a time constant of 10 seconds then this is quite feasible. However, typical process plant equipment may have a time constant any where from a few minutes to several hours. It would just take too long to carry out this trial and error method.

The methods that we are going to examine were developed by engineers in to process industry to give a reasonable estimate of the tuning parameters in the minimum of time.

2. Ziegler-Nichols Tuning Methods

Ziegler and Nichols published their famous paper way back in 1942. The paper describes two methods based upon empirical rules. These methods have been widely used within the process industry. However, better methods now exist.

Reaction curve method

The Ziegler-Nichols reaction curve method is based on a simple open-loop (manual control) step response test.

In practice the controller is switched to manual operation and with the plant at or near its normal operating condition, a small step change in control effort is applied. The resulting response, called the reaction curve, is used to estimate the effective delay, D, and maximum slope of the response, N (figure 1).

The Z-N reaction curve recommended settings are shown in table 1. Unfortunately, these settings often give very poor results and Brambilla’s method (section 3) gives much better performance.

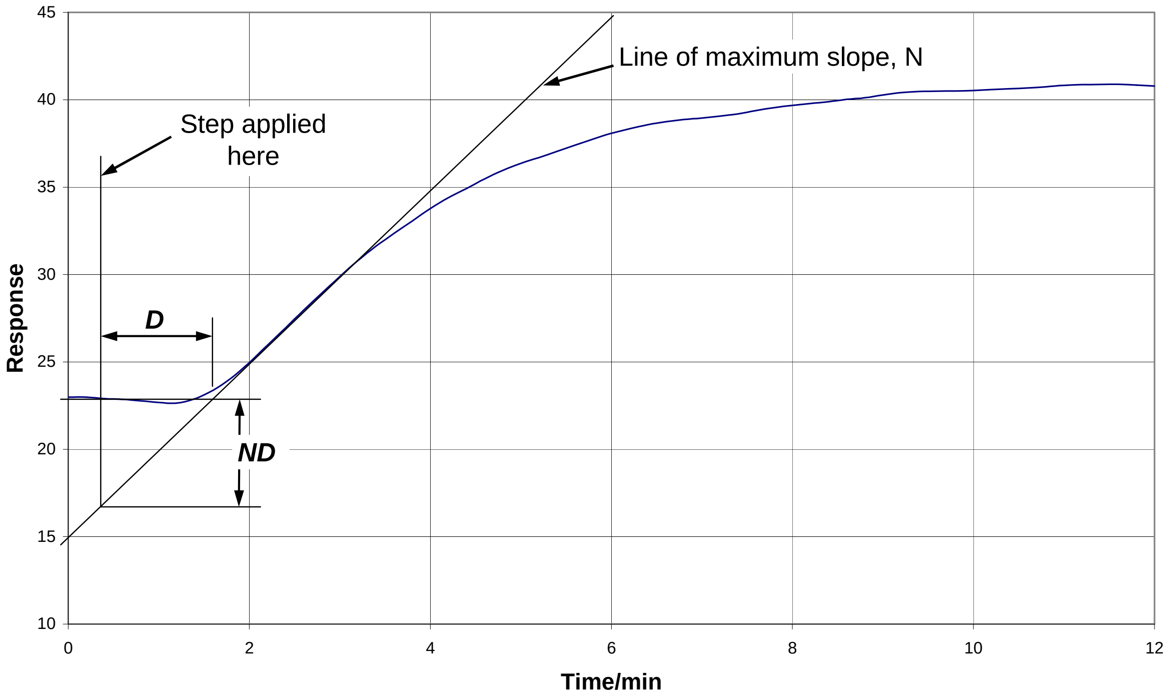

Figure 1 – The Ziegler-Nichols reaction curve method

The settings recommended by Ziegler-Nichols are shown below in table 1:

Table 1 - Ziegler-Nichols reaction curve settings

Type of controller	Proportional band, PB	Reset time, Tr	Derivative time, Td
P	$\frac{ND}{\Delta u}$	—	—
P+I	$\frac{ND}{0.9\Delta u}$	$\frac{D}{0.3}$	—
P+I+D	$\frac{ND}{1.2\Delta u}$	$\frac{D}{0.5}$	$\frac{D}{2}$

N = maximum slope of reaction curve as a percentage of the measurement range.
D = Effective delay.
Δu = Fractional change at process input.

As an example consider a temperature controller with a range of 0 to 50°C. The response shown in figure 1 was obtained with the controller in manual mode and by suddenly increasing the controller output by 20%.

The effective delay, *D*, from figure 1 is approximately 1.2 minutes and *ND* is approximately 6°C, which as a fraction of the controller range is 6/50 = 0.12. The fractional Δu is 0.2.

The recommended settings for a three-term controller thus would be:

$$\text{PB} = \frac{ND}{1.2\Delta u} = \frac{12\%}{1.2 \times 0.2} = 50\%$$
$$T_r = \frac{D}{0.5} = \frac{1.2}{0.5} = 2.4 \text{ minutes}$$
$$T_d = \frac{D}{2} = \frac{1.2}{2} = 0.6 \text{ minutes}$$

Continuous cycling method

The Ziegler-Nichols continuous cycling method uses results from a simple closed-loop step response test to estimate the controller settings. This normally gives far better results than the reaction curve method. However, it does take longer to carry out and involves placing the plant into continuous oscillation, which may not be acceptable.

The method involves closed-loop step response tests with the reset and derivative actions switched out. To do this we must set the integral time to its maximum value and the derivative time to its minimum value.

Starting with a low gain (i.e. wide PB) and the plant at its normal operating point, we must switch to automatic mode and make a small change to the reference or set-point. If the response settles down (e.g. figure 2a) the gain is below the critical value, i.e. the PB is above the critical value. We must then switch back to manual, restore the base settings and try again with an increased the controller gain (i.e. reduced PB). Eventually, the controller will produce a response which just continues to oscillate continuously. Note that it is very easy to go too far and think that you have reached the critical value when in fact you have passed it. This is because most processes will show a limit cycle even when completely unstable.

The settings recommended by Ziegler-Nichols are shown in table 2:

Table 2 - Ziegler-Nichols continuous cycling method settings

Type of controller	Proportional band, PB	Reset time, Tr	Derivative time, Td
P	$2PB_u$	—	—
P+I	$2.2PB_u$	$\frac{T_u}{1.2}$	—
P+I+D	$1.7PB_u$	$\frac{T_u}{2}$	$\frac{T_u}{8}$

PB_u = Ultimate proportional band.
T_u = Ultimate period.

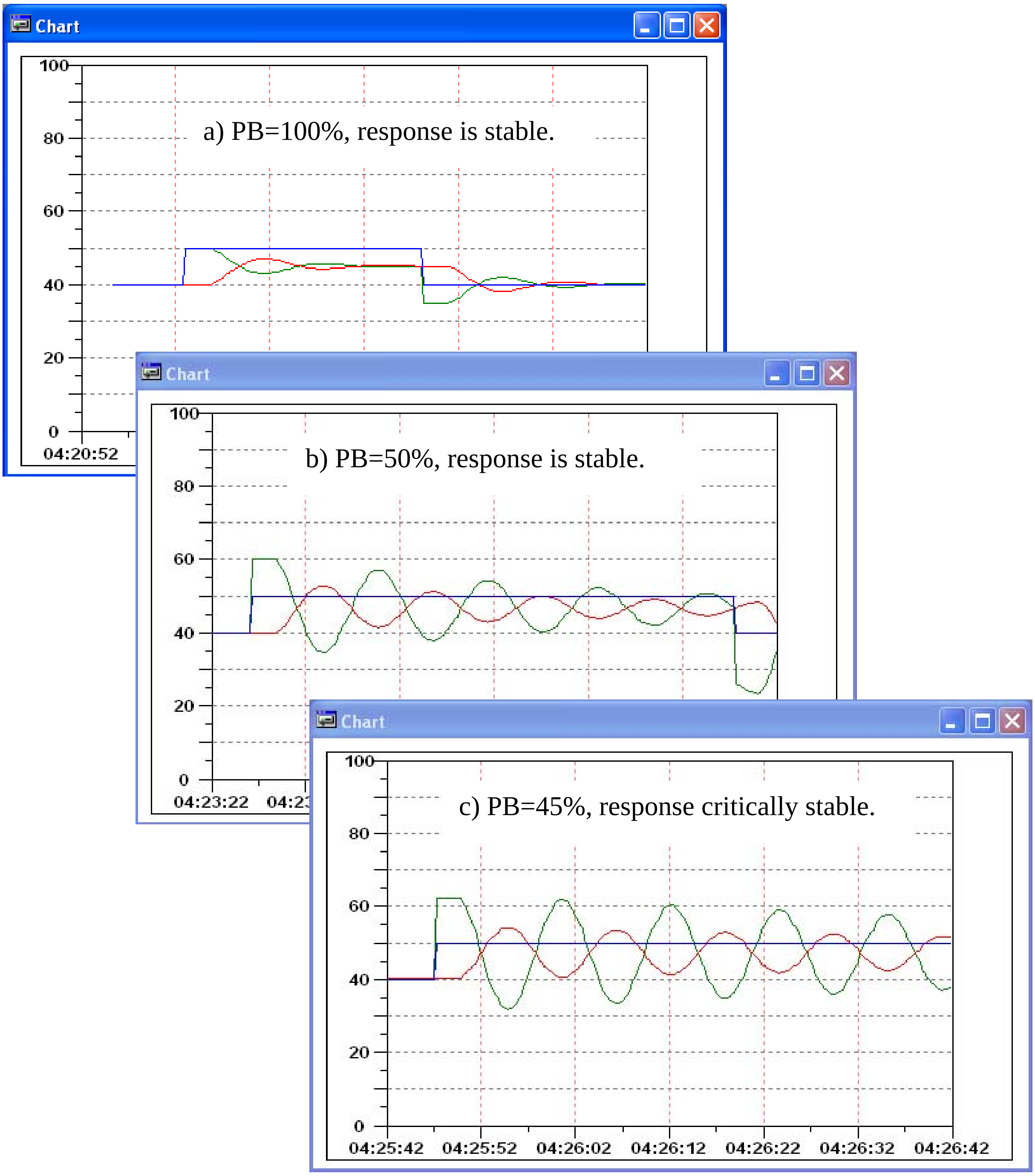

Figure 2 – Typical results from a continuous cycling tuning exercise

When critical stability is reached, we must note the PB and the period of oscillation. These values are called the “Ultimate PB”, PB_u, and “Ultimate period”, T_u.

For the example shown in figure 2, we have almost reached instability with PB = 45%. The resulting period of oscillation can be averaged over 5 cycles as about 53s/5 = 10.6s. Thus:

$PB_u = 45\%$ and $T_u = 10.5\text{s}$

The Z-N recommended settings for a PID controller for this plant are thus:

$PB = 1.7PB_u = 1.7 \times 45 = 76.5\%$, say 75%

$Tr = T_u/2 = 10.6/2 = 5.3s$, say 6s

$Td = T_u/8 = 10.6/8 = 1.325s$, say 1.3s

Figure 3 shows the response of this plant to a set-point change and load change with these settings.

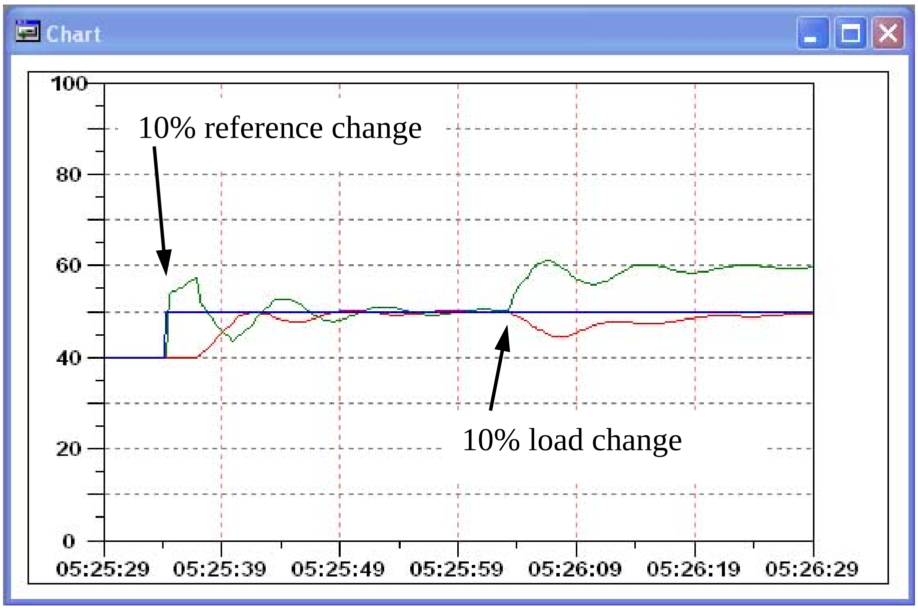

Figure 3 – Response of a PID controller tuned according to Z-N continuous cycling method

3. Brambilla's Tuning Method

This method is an alternative to Ziegler-Nichols' methods that was developed by A Brambilla of the University of Pisa, Italy in 1990 ("Robust tuning of conventional controllers", A Brambilla et al, Hydrocarbon Processing, November 1990.

The method, like the Ziegler Nichols reaction curve method, is based on an open-loop test. Open-loop tuning methods have the advantage over continuous cycling of minimising the disruption to the plant.

A step response test is carried out on manual mode (open-loop) from which three values are estimated:

K_P – the plant gain
T_D – the effective plant time delay,
A – the effective plant time constant, i.e. the time for the plant to reach 63.2% of the steady-state change after the time delay has elapsed

The method uses a parameter, *B*, which represents the desired effective closed-loop time constant. The recommended value of *B* is $A/2+T_D$, but a faster or slower response can be achieved by reducing or increasing *B* from this value. The recommended settings are:

$$K_c = \frac{1}{K_p}\frac{A+T_D/2}{B+T_D}$$

$$T_r = A+T_D/2$$

$$T_d = \frac{AT_D}{2A+T_D}$$

It is interesting to note that the reset and derivative times are independent of *B*, thus changing *B* is equivalent to adjusting the controller gain or proportional band. Also note that the calculated values are applicable to P, PI or PID control, i.e. the same reset-time is employed in both PI and PID control.

As an example, we will calculate the Brambilla settings for the plant that we were controlling previously using ZN settings. The open loop response of this plant is shown in figure 4.

Figure 4 – The open-loop step response of the example plant

In this case the plant gain is simply 1, the delay is about 2s and the effective time constant is about 2.5s.

The settings recommended by Brambilla are thus:

$$B = \frac{A}{2}+T_D = \frac{2.5}{2}+2 = \underline{3.25s}$$

$$K_c = \frac{1}{K_p}\frac{A+T_D/2}{B+T_D} = 1.\frac{2.5+1}{3.25+2} = \frac{3.5}{5.25} = \underline{0.667}, \quad \text{i.e.} \quad \text{PB} = \frac{100\%}{0.667} = \underline{150\%}$$

$$T_r = A + \frac{T_D}{2} = 2 + 1 = \underline{3s}$$

and $$T_d = \frac{A.T_D}{2A + T_D} = \frac{2.5 \times 2}{5 + 2} = \frac{5}{7} = \underline{0.714s}$$

Figure 5 shows the resulting step and load response with these settings. You can see that the performance is certainly no worse than the the ZN continuous cycling method.

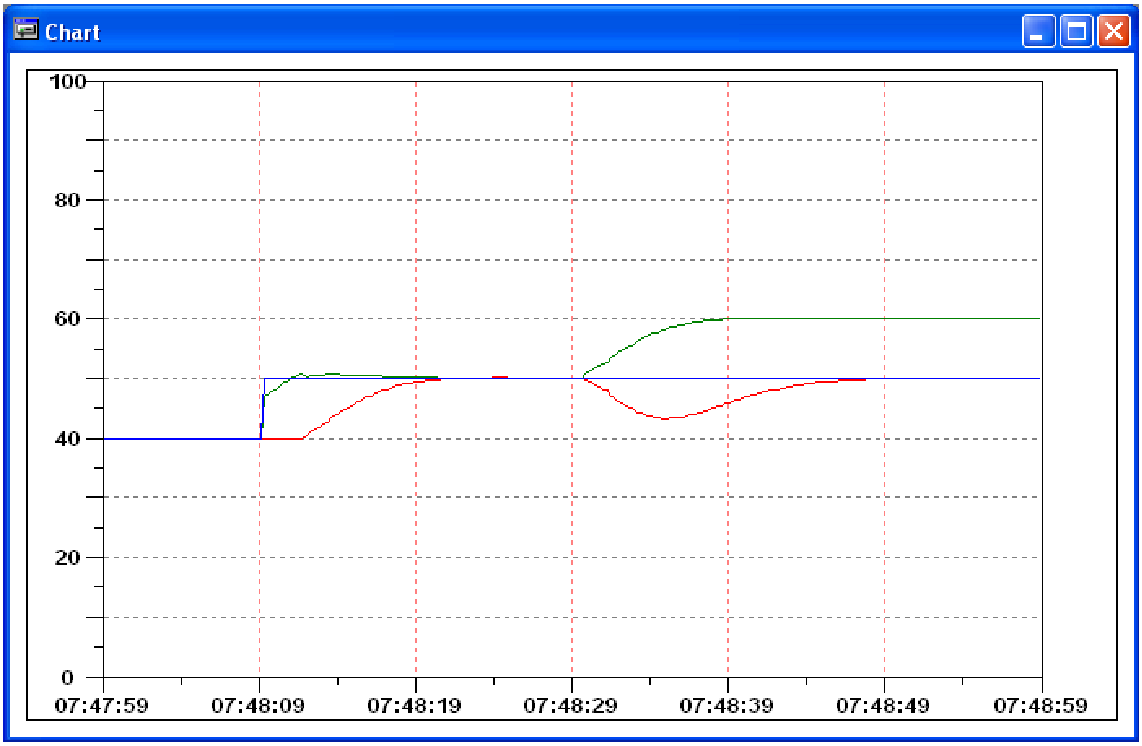

Figure 5 – Response of a PID controller tuned according to Brambilla's method

As another example, consider the plant response shown in figure 6.

The plant gain is estimated as: $$K_p = \frac{\Delta C}{\Delta U} = \frac{63 - 37}{55 - 45} \approx 2.6$$

The effective plant delay is approximately: $T_D \approx 50s$

The effective time constant is found by determining the 63% point on the response, i.e. $0.63 \times (63 - 37) = 16.4$. The time for the response to rise from the initial value by 16.4 is thus:

$$A \approx 130 - 50 = 80s$$

The recommended closed-loop time constant is: $A/2 + T_D = 90s$. Giving, for a PID controller:

$K_c = 0.288$ (PB = 347%); $T_r = 105s$; $T_d = 19s$.

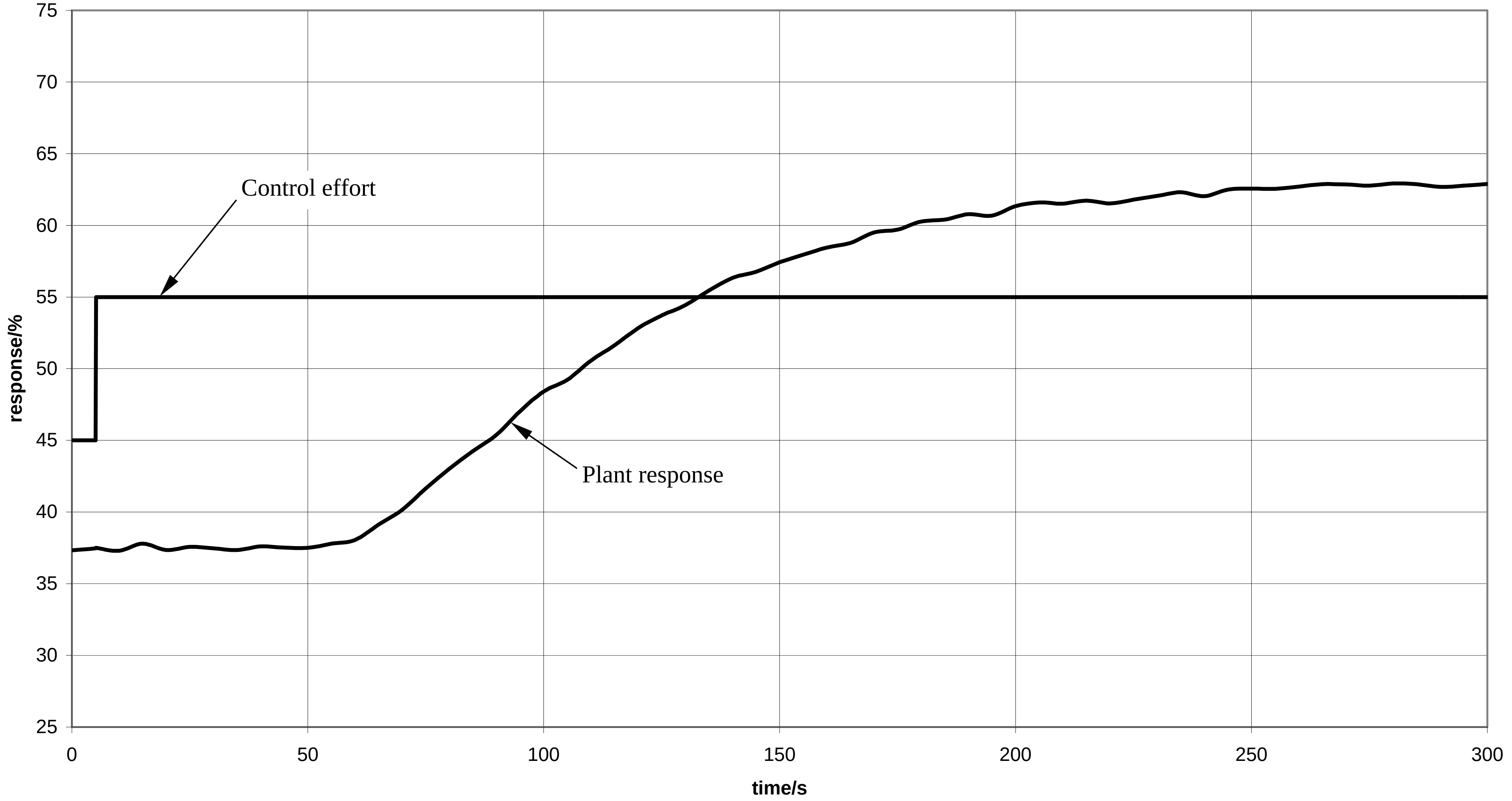

Figure 6 – Reaction curve of a process plant