Control and properties of processes with recycle dynamics

Santiago Castro Chans

LUND UNIVERSITY

Department of Automatic Control

MSc Thesis
ISRN LUTFD2/TFRT--6007--SE
ISSN 0280-5316

Department of Automatic Control
Lund University
Box 118
SE-221 00 LUND
Sweden

Printed in Sweden by Tryckeriet i E-huset
Lund 2016

Abstract

This project discusses the effects of recycle streams on the dynamics and performance of chemical plants. The questions addressed are: can the current industry standard tuning methods still be applied to systems with recycle, and if not, how can they be modified? This is approached by analysing the arrest time tuning method when applied to an integrating process with and without recycle. The results show that the integrating model does not capture all the relevant dynamics of the integrating process with recycle. Consequently a new model, and an easy tuning method for the industry standard controllers, is proposed.

Acknowledgements

I want to start thanking Perstorp AB for the opportunity to make this master thesis in collaboration with them, for providing me an office and access to their facilities. It has been a pleasure for me to see how this big company works and to be part of their day by day during the last six months.

I am deeply grateful to Mohammed Adlouni for all the endless discussions and the help. He has always the door open for me and was always available to take a meeting no matter how busy he was.

I want to express my gratitude to Krister Forsman and Johan Rönnberg for sharing all their extensive knowledge and for giving me so useful advices and comments.

I would like to thank Richard Pates for his time, patience and also for giving me another perspective in to the problems that i approached under my master thesis.

I want to dedicate this project to the persons most important in my life: my son Leo and my partner Evelina. They are my inspiration and strength to keep fighting even when the problems seem to be overwhelming.

I don´t want to forget to thank my family. Their unconditionally support, love and kindness make me admire them more and more everyday.

Nomenclature

α: recycle rate
L : time delay
k_v : speed gain
K_c : controller gain
T_i : integral time
P : process
C : controller
H: recycle dynamics
T_a : arrest time
K_u : ultimate gain
$\varphi_{m,max}$: maximum phase margin
$k_{v,ult}$: ultimate speed gain
$k_{v,m}$: the speed gain of the IPZ model

Contents

1. Introduction **1**
1.1 Background 1
1.2 Purpose and Goal 1
1.3 Literature review 2
1.4 Base Case 3
2. Base case without recycle **7**
2.1 Process model 7
2.2 Control 7
3. Base Case with recycle **12**
3.1 Process model with recycle dynamics 13
3.2 Phase margin analysis 15
3.3 T_a tuning for the integrating process with different recycle dynamics 18
3.4 Different possible tuning scenarios 23
4. Suggested improvements **29**
4.1 IPZ model approximation 29
4.2 Tuning of the IPZ model 31
4.3 Some examples 32
4.4 Is the IPZ tuning robust for the integrating process with recycle? 43
4.5 Conclusions 46
A. Maximum phase lag calculations **48**
B. Boundaries analysis of the recycle term **49**

B.1 Amplitude 49
B.2 Phase 49

Bibliography **51**

1

Introduction

1.1 Background

For economical and environmental reasons recycle streams are very common in chemical plants. They allow to save product and energy but create an interaction between the different parts of the plants which leads to a very difficult task in terms of operability and controllability. For these reasons a better understanding of recycle systems is the key for future improvements in this field.

1.2 Purpose and Goal

The main purpose of this master thesis is to give an overview and analysis about the properties of recycle systems to help control engineers to better understand the behaviour of processes affected by recycle. The analysis should also clarify how the recycle system differs from a similar system without recycling.

The master thesis starts with an extensive analysis of the base case (integrating process) with and without recycle dynamics. The integrating process is one of the most common processes in the industry nowadays, that's why, it is so relevant. The base case analysis will lead us to better understand if the methods used to tune controllers without recycle are still suitable when the process is affected by recycle.

The thesis should by its completion have resulted in presenting of the analysis results for the studied cases as well as guidelines and recommendations regarding modeling and control of systems with recycle dynamics. At the same time the goal is to provide a guide with the steps recommended to follow for such a systems in order to perform a tuning that improves the performance and stability of the plant.

1.3 Literature review

Recycle operations often leads to poor dynamics as is shown by Denn and Lavie [Denn and Lavie, 1982]. A major conclusion which can be extracted from this paper is that the time response of the process with recycle is considerably longer than the case without recycle in the forward path. Luyben [Luyben, 1993a] shows the effects of varying the recycle parameters in a very simple process with recycle in open loop and in closed loop. In the next articles of the same series Luyben [Luyben, 1993b] [Luyben, 1993c] [Luyben and Tyreus, 1993] compares different reactor/stripper (system with internal recycle) configurations in order to achieve better controllability of the plant. As a generic rule Luyben suggests to fix the recycle flow rate in order to avoid disturbances and to minimize the effects of recycle.

Taiwo [Taiwo and Krebs, 1996] proposed the use of a recycle compensator using IMC (internal model control) to design robust controllers for the compensated plant. Scali and Ferrari in [Scali and Antonelli, 1996] discuss possible improvements in the recycle compensator introduced by Taiwo.

Skogestad [Morud and Skogestad, 1996], in an effort to understand how heat integration and product recycle affects the dynamics of the plant, studied the effects of the different types of interconnections in the dynamics of the open loop system and provided a guide of how the dynamics of the process changes with the different kind of interconnections.

There is a large number of papers about recycle systems however nothing similar to our base case (figure 3.1) was found under my literature research. All the literature found treats the case when the recycle is applied to the measured output (see figure 1.1). In our base case, as is detailed in the report (see section 3.1), the recycle affects in feedforward or parallel path the process by affecting the speed gain after a certain time L.

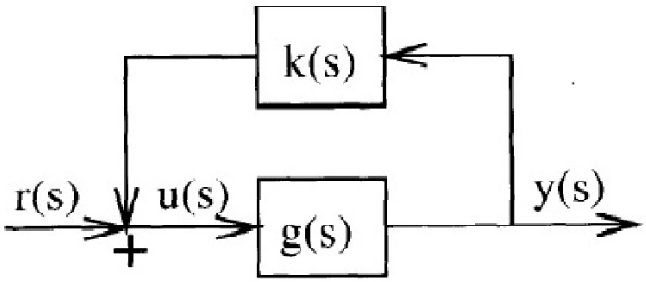


Figure 1.1: Most typical case of recycle found under the literature review. Taken from [Morud and Skogestad, 1996].

1.4 Base Case

As starting point for the analysis a simplified version of a recycle system is selected. The base case is only one tank with outflow and inflow. A fraction of the outflow (α) from the tank is recycled as can be seen in the figure 1.2. For simplicity it is assumed that the output of the controller is the same as the flow through the valve. To put it with other words the control signal of the level controller is the outflow of the tank. One thing to mention here is that the recycle flow is delayed a certain time L. The base case is simple enough to allow in-depth analysis but still include the relevant aspects of recycle systems. The controller for the base case is a PI controller tuned according to a defined tuning method, i.e. arrest time tuning. Only step disturbances are considered for the base case. The PI controller maintains the level constant in the tank by manipulating a valve which controls the outflow of the tank and in turn the recycled rate.

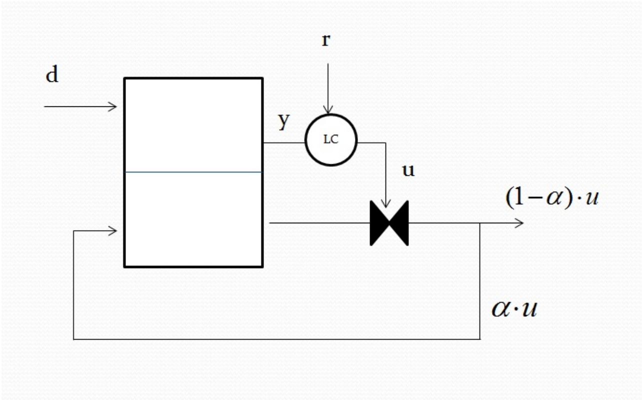


Figure 1.2: Tank with recycle. Where LC is a level controller.

The base case could represent two different cases of recycle in form of heat integration. In both cases the tank with recycle is a representation of the energy flow in a column with a heat exchanger. These two systems are very common design cases in Perstorp AB. For this reason it is very important to understand the effect of heat integration in the dynamics of the process.

Case 1. Heat integration from the top of the column The outflow from the tank (term u(1- α) in figure 1.2) represents in this case the outflow of energy from the system, more concretely, the energy in form of heat that can not be transferred to the fresh feed in the heat exchanger. The input of the tank (d) represents in this case the energy inflow in to the system. This is the energy supplied for the reboiler plus the energy in form of heat from the fresh feed. The recycle in this case comes from the reflux drum.

The heat energy in the reflux drum hold up is used to heat up the fresh feed in the heat exchanger. Here it is assumed perfect control in the flow controller which manipulates the valve of the reboiler.

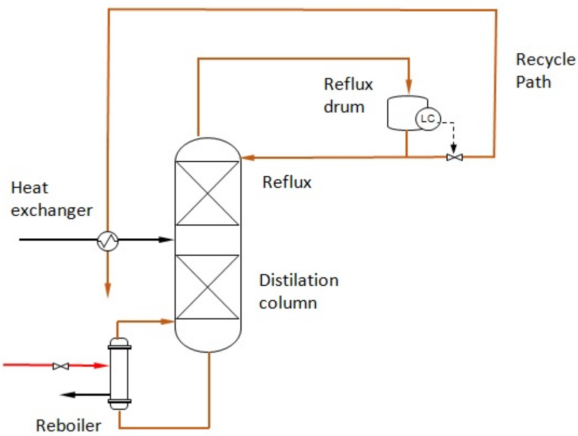


Figure 1.3: Column with heat integration and recycle from the reflux drum.

Case 2. Heat integration from the bottoms It is very similar to Case 1 but the recycle connection used to heat up the fresh feed in to the heat exchanger comes from the bottoms of the column (see figure 1.4). It is assumed perfect control in the level controller of the reflux drum and in the flow controller of the reboiler.

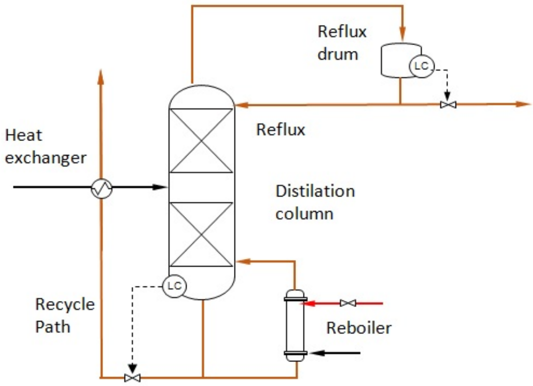


Figure 1.4: Column with heat integration and recycle from the bottoms.

2

Base case without recycle

The base case without recycle can help us to better understand the behaviour of the case with recycle from a theoretical point of view. In this chapter the integrating process under arrest time tuning is analyzed. The purpose of this chapter is to act as a point of reference for the chapter in which the recycle is introduced under the same tuning conditions.

2.1 Process model

The process can be modelled in different ways but for matters of simplicity an integrating process was selected with a certain speed gain k_v. The integrating process is a very simple model but one of the most common in industry.

$$P(s) = \frac{k_v}{s} \tag{2.1}$$

2.2 Control

PI controller

This is the most common controller in the industry nowadays. The controller has two part:

- The P-part is the proportional part of the controller also called the controller gain. Increasing K_c results in faster control and a reduction of the stationary error but with the cost of decreasing the stability margins.

- I-part is the integral part of the controller. Increasing the I part ($\frac{K_c}{T_i}$) results in a faster response in low frequencies along with decrease in the phase. This implies worse robustness in the closed loop transfer function.

The ideal formula for the PI controller in continuous time is:

$$u(t) = K_c e(t) + \frac{K_c}{T_i} \int_0^t e(t)dt \tag{2.2}$$

Tuning of the PI controller for the integrating process (Arrest time tuning)

This is one of the most popular methods in industry to tune PI controllers for integrating process. This method is also known as T_a tuning and has three steps [Forsman, 2005].

- Identify the process speed gain (k_v): This can be done experimentally using the data for step. In this step as it is explained more in detail in the coming sections it is crucial to take a long enough step to capture all the process dynamics.

- Decide the desired arrest time (T_a): T_a is related with the position of the poles for the close loop transfer function. For more details about the derivation of the T_a tuning and the properties see the next two paragraphs. The physical interpretation of the T_a tuning is very simple. It is the time that it takes for the output (y) to come back in the right direction after a step disturbance (d).

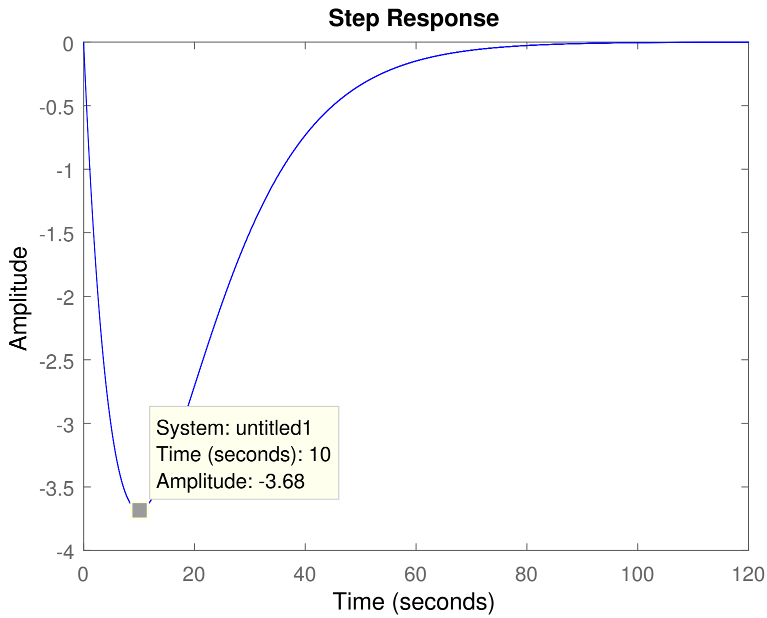


Figure 2.1: Physical interpretation of the arrest time concept for T_a=10.

- Calculate the controller parameters (K_c and T_i). For a derivation see the next subsection.

$$K_c = \frac{2}{k_v T_a}, T_i = 2T_a \tag{2.3}$$

The next two paragraph are based on [Forsman, 2015]

Derivation of the T_a-tuning for the integrating process The closed loop transfer function from r-y for the integrating process with a PI a controller has the following equation:

$$G_{ry}(s) = k_v K_c \left(\frac{sT_i + 1}{s^2 T_i + k_v K_c T_i s + k_v K_c}\right) \tag{2.4}$$

with the characteristic equation

$$s^2 + k_v K_c s + \frac{k_v K_c}{T_i} = 0 \tag{2.5}$$

So if we want to place both poles in $-1/T_a$ the characteristic equation should be

$$(s + \frac{1}{T_a})^2 = 0 \tag{2.6}$$

or if it is expanded

$$s^2 + \frac{2}{T_a}s + \frac{1}{T_a^2} = 0 \tag{2.7}$$

Now comparing the equation 2.5 and 2.7 the controller parameters needed to place a double pole in -1/T_a are:

$$K_c = \frac{2}{k_v T_a}, T_i = 2T_a \tag{2.8}$$

For a T_a-tuned process the close loop transfer function from r-y becomes

$$G_{ry}(s) = \frac{2sT_a + 1}{(sT_a + 1)^2} \tag{2.9}$$

and the transfer function from the disturbance to the output of the process (d-y) is

$$G_{dy}(s) = \frac{k_v s}{(sT_a + 1)^2} \tag{2.10}$$

Properties of the T_a-tuning The closed loop unit step response is obtained after an inverse Laplace transform of the transfer function 2.9 and is equal to

$$y(t) = 1 + (\frac{t}{T_a} - 1)e^{-\frac{t}{T_a}} \tag{2.11}$$

evaluating this equation in T_a and $2{\cdot}T_a$

$$y(T_a) = 1, y(2T_a) = 1 + e^{-2} \simeq 1.135 \tag{2.12}$$

The derivative of the step response is

$$\dot{y}(t) = \frac{1}{T_a^2}(2T_a - 1)e^{-\frac{t}{T_a}} \tag{2.13}$$

so that when t=$2T_a$

$$\dot{y}(2T_a) = 0 \tag{2.14}$$

These properties can be seen in the step response from the controller's reference to the output of the process (see figure 2.2).

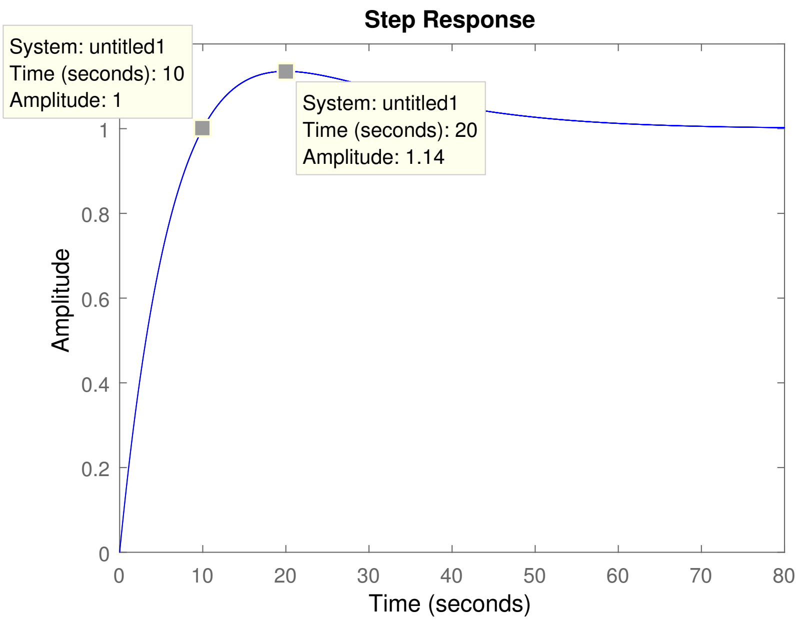


Figure 2.2: Properties of the T_a tuning for T_a=10.

3

Base Case with recycle

The aim of this chapter is to analyze and try to answer the following questions

1. How does the integrating process change under different recycle dynamics?

2. How good is the control performance for T_a tuning in the integrating process with different recycle dynamics?

3. Is the T_a tuning method still suitable with regards to control performance?

4. Is a new model and tuning method needed?

3.1 Process model with recycle dynamics

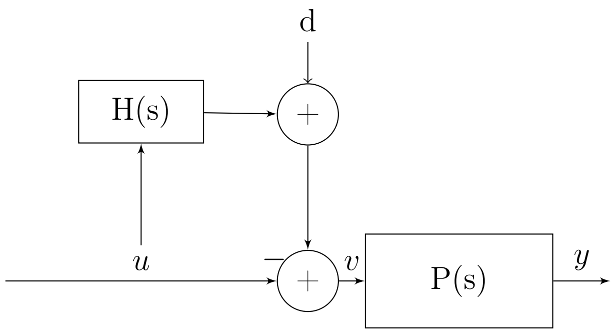


Figure 3.1: Block diagram of the process with recycle dynamics.

The transfer function for the process with recycle is given by the following equation. Here α represents the rate of outflow recycled to the tank and L the time delay.

$$P(1-H) = \frac{k_v(1-\alpha e^{-sL})}{s} \tag{3.1}$$

Where

$$H(s) = \alpha e^{-sL}$$

The recycle affects the process dynamics by decreasing the gain of the open loop system by a factor 1- α. As it is shown in the figure 3.2 this happens after the time delay. This phenomenon makes very difficult to control a process that has two different speed gains, one before the time delay (k_v) and one after (called in this paper ultimate speed gain or $k_{v,ult}$). As it is analyzed later in this report, it is impossible to observe the speed gain of the process with recycle ($k_{v,ult}$) if L is larger than the step time. Another interesting case is when the delay is a lot of shorter than the time of the step. Here the control engineer doesn't observe the speed gain of the process without recycle (k_v). All these circumstances make it very hard for the control engineer to perform a step that captures all the dynamics of the process. The goal with the modelling phase is to build an easy model that reflects the process as well as possible.

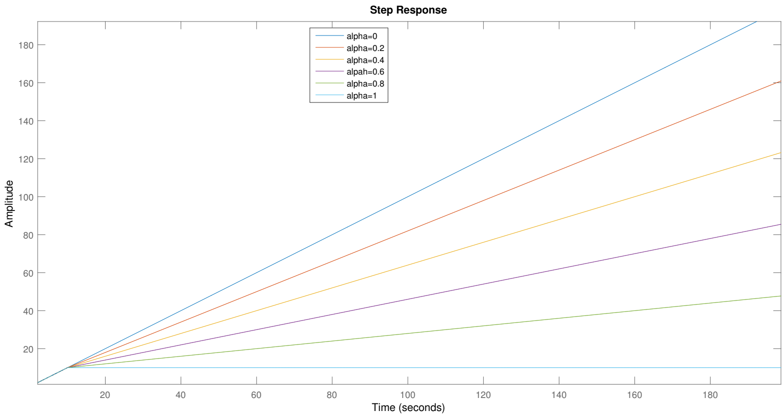


Figure 3.2: Open loop step response with various recycle gains. Recycle delay L=10.

The figure 3.2 shows how the recycle gain α affects the speed gain after the time delay. It is interesting with the case when α equals to one because the speed gain of the process with recycle will be zero after the time delay. This is a very unrealistic situation because for example in the case of heat integration there is always energy losses in the heat exchanger.

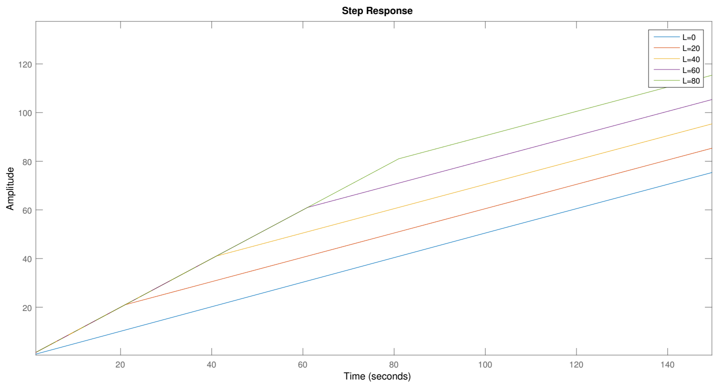


Figure 3.3: Open loop step response with various recycle dynamics. Recycle gain $\alpha = 0.5$.

There are no fundamental limitations on how fast or slow the process with recycle can be controlled since there is no unstable pole and the recycle term can be approximated as a LHP zero. The only limitation is in the uncertainty introduced in the phase by the recycle in the integrating process in high frequencies (figure 3.5). This uncertainty puts an upper bound in terms of how robust the PI controller can be for the integrating process with recycle. This is explained in more detail in the next section.

3.2 Phase margin analysis

The goal of this section is to analyze the phase lag introduced by the recycle to the open loop system and give some equations to calculate the maximum phase margin ($\varphi_{m,max}$) that can be obtained with a PI controller for the integrating process with recycle. This will give us an idea of how robust our tuning is in comparison with the maximum phase margin that can be achieved for an integrating process with recycle.

The loop gain for the integrating process with a PI controller is:

$$PC = k_v K_c (\frac{sT_i + 1}{s^2 T_i}) \tag{3.2}$$

It is well known that the phase of an integrating process and PI controller goes from -180 to -90° as shown in figure 3.4. This means that with the best possible tuning the recycle term (1-αe^{-sL}) has to introduce a phase lag smaller than -90 ° for the closed loop system to be stable.

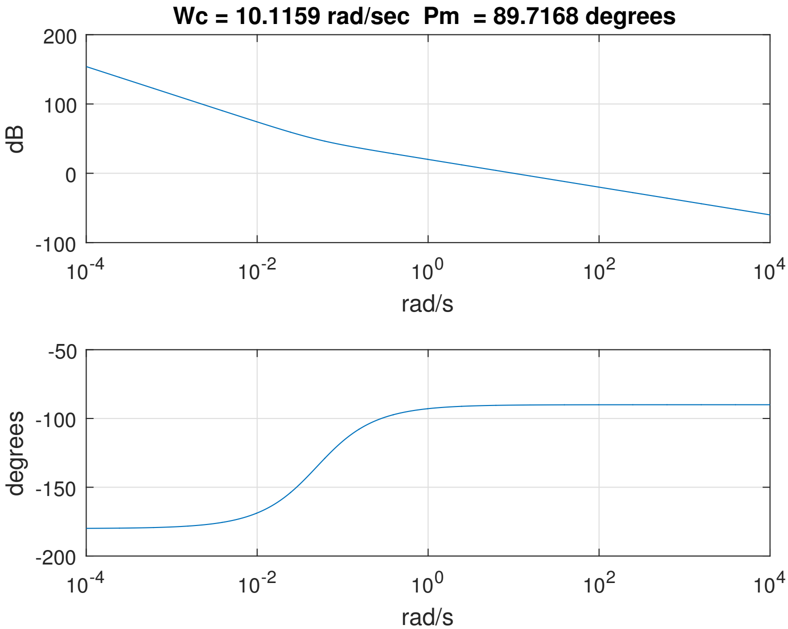


Figure 3.4: Integrating process with PI controller.

The phase of the recycle term is given by the equation 3.3 and it is displayed in the figure 3.5.

$$\varphi_{(1-H)} = arg(1 - \alpha e^{-sL}) = atan(\frac{\alpha sin(\omega L)}{1 - \alpha cos(\omega L)}) \tag{3.3}$$

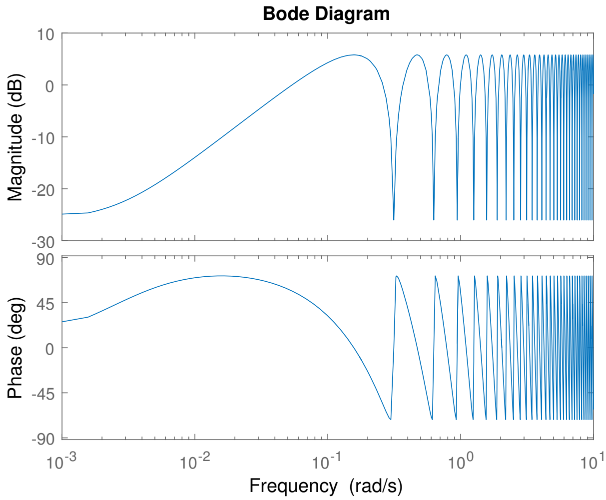


Figure 3.5: Bode plot of the 1-H term with α=0.95.

The maximum value of the phase lag introduced by the recycle term is achieved when

$$\frac{d\varphi_{(1-H)}}{d\omega} = 0 \tag{3.4}$$

After some calculations (for the details see appendix A) it is obtained the equation for the maximum phase lag introduced by the recycle that is

$$\varphi_{max,(1-H)} = atan(\frac{\alpha}{\sqrt{1-\alpha^2}}) \tag{3.5}$$

Now the maximum phase margin which can be obtained for the open loop system with recycle, taking in to account the uncertainties in the estimation of L is given by

$$\varphi_{max,PC(1-H)} = 180 + \varphi_{max,PC} - \varphi_{max,(1-H)} \tag{3.6}$$

In this section the upper bound for how robust the PI controller for the integrating process with recycle is numerically calculated in terms of phase margin. The next step is to show how the method used to tune PI controllers for integrating process (T_a tuning) performs for different types of recycle dynamics.

3.3 T_a tuning for the integrating process with different recycle dynamics

Performance of a PI controller tuned accordingly to the existing tuning method for the integrating process (T_a tuning) are evaluated for different recycle dynamics. The results are compared for different types of recycle rate (α =0.2 ,0.5 and 0.8) and time delays (L =0.2, 20 and 50). It is worth to mention that the step response that it is displayed in the following six figures are for the case when the control engineer performs a short step (time step $<$ L) and the recycle dynamics was not observed ($k_{v,ult}$). In this case the control engineer will use the speed gain of the integrating process without recycle (k_v) in the T_a tuning method. For the t>L (when the recycle appears) the speed gain of the process ($k_{v,ult}$) is a factor 1-α smaller than the speed gain used to tune controller. As a result of this fact the step response observed will not be as expected for a T_a tuning.

The step response from the reference to the measured output are shown in the figures 3.6, 3.7 and 3.8.

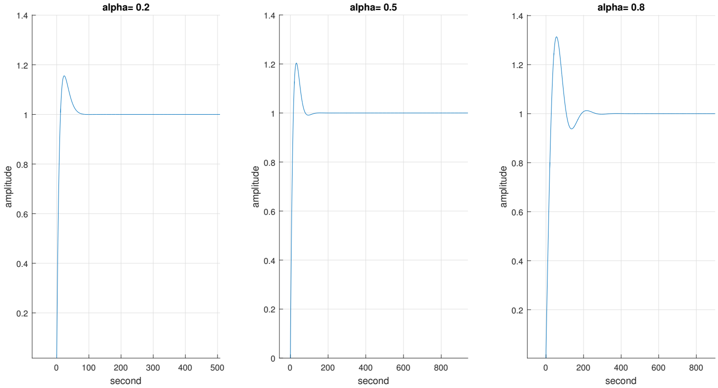


Figure 3.6: Step response r to y for different α with L=0.2, T_a=10 and k_v=1.

For very small L and recycle rate the T_a tuning method gives almost the expected performance but a little bit overshooted (figure 3.6) because the difference between the k_v used in the tuning method and the speed gain of the process is very small for t > L. As the α increases the step response looks more overshooted because the difference between the $k_{v,ult}$ (the speed gain after the delay) and the k_v used in the tuning method increases. As a consequence of this the K_c used in the controller according to the T_a tuning method is going to be a factor 1-α smaller than it should for t > L.

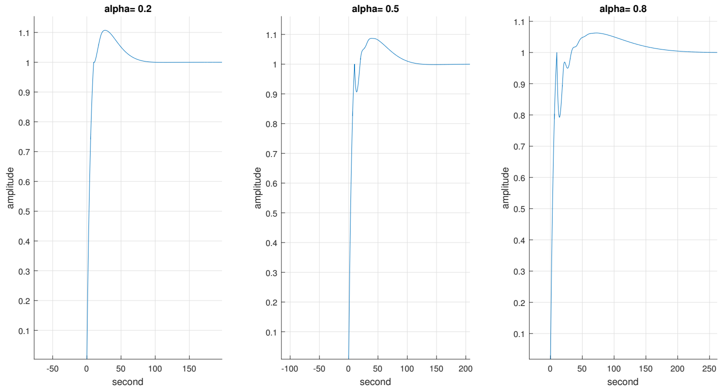


Figure 3.7: Step response r to y for different α with L=20, T_a=10 and k_v=1

For very large values of L ,in comparision with the setting time, the step response performs as expected because the speed gain used in the T_a tuning is the same of the speed gain of process. The peaks that it is observed in the figure 3.8 are the recycle acting as a disturbance periodically in the process. These disturbances, as we called it, come in periods of L and the magnitude depends primarily on two factors the magnitude of α and the gain of the controller.

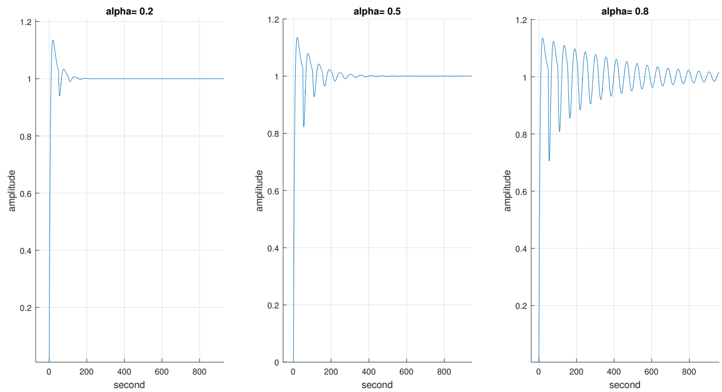


Figure 3.8: Step response r to y for different α with L=50, T_a=10 and k_v=1.

The step response from disturbance to the measured output are shown in the figures 3.9 and 3.10.

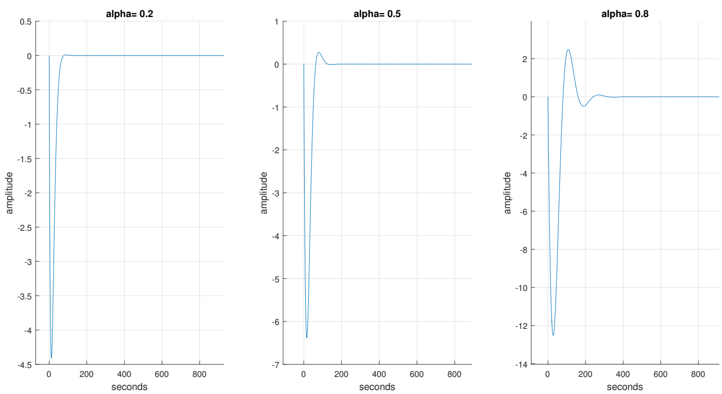


Figure 3.9: Step response d to y for different α with L=0.2, T_a=10 and k_v=1.

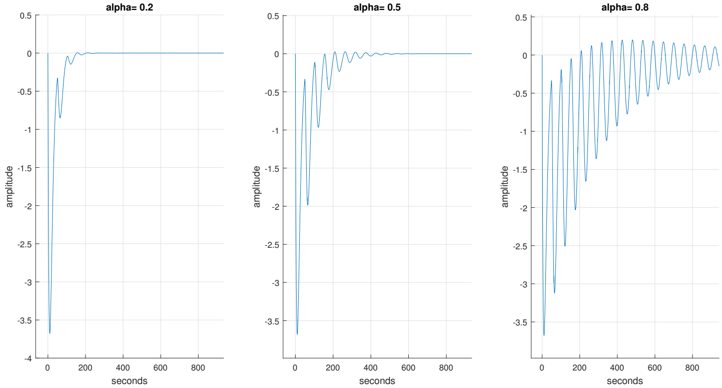


Figure 3.10: Step response d to y for different α with L=50, T_a=10 and k_v=1.

As the last part of the performance analysis for different recycle dynamics three Nyquist plots are displayed (see figure 3.11). These parametric plots shows how the real and imaginary part of the open loop change as a function of the frequency. The controller selected is a PI controller with T_a tuning according with the discussed earlier (no compensation factor included in the speed gain).

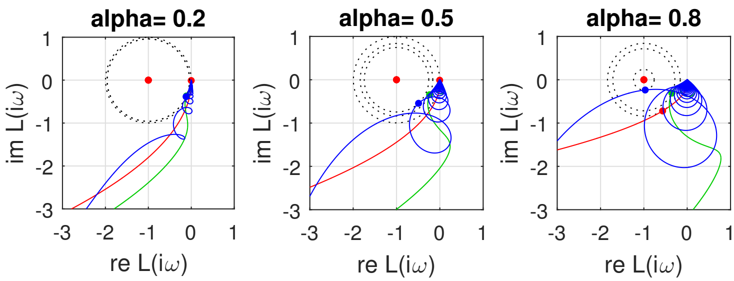


Figure 3.11: For T_a=10 and k_v=1. Recycle delay L=0.2 (red), L=10 (green) and L=50 (blue).

3.4 Different possible tuning scenarios

The goal of this section is to give an overview of the different scenarios that a control engineer can find when a step is performed in the integrating process with recycle. It is classified in two different scenarios that depends on the relation between L and the step time. In the scenarios where the change in the speed gain is observed (scenario 2) it is recommended that the control engineer will wait a time that it is longer than $2L$.

Another question that this section approaches is if the tuning methods for integrating process are still suitable for the case with recycle and the possible consequences of the different choices of T_a and speed gain in the tuning method. When the T_a tuning method is used in the integrating process with recycle the control engineer has to make a decision about which of the two speed gains observed (if both gains are observed) will be used in the tuning method.

Step time $< L$

In this case the $k_{v,ult}$ is not observed. The control engineer has three different choices for the T_a but in all of them the k_v used to tune the controller is the speed gain of the process without recycle. This is called arrest time tuning without speed gain compensation.

1. $T_a <$ L

2. $T_a \simeq$ L

3. $T_a >$ L

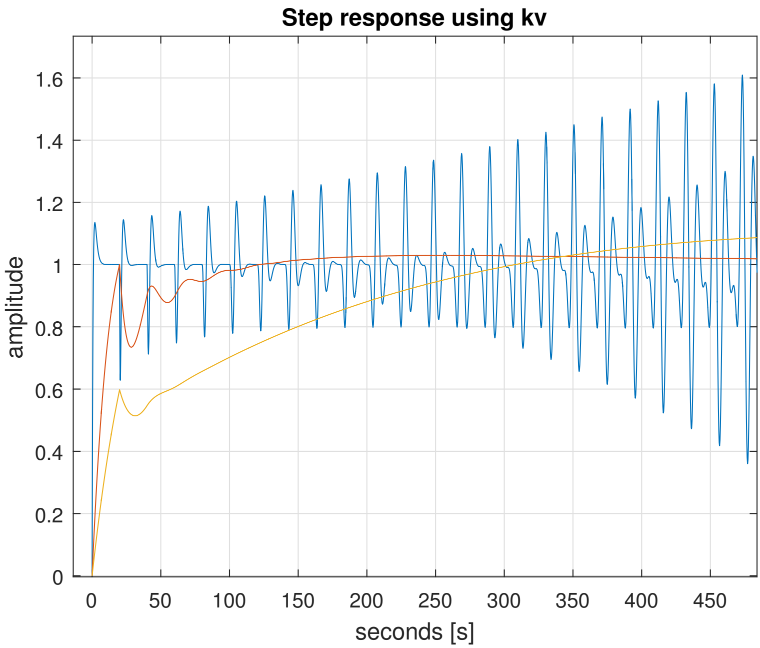


Figure 3.12: Step response of the closed loop process with recycle for α=0.95, L=20 and T_a= 1(blue), 20(red) and 50 (orange).

This is very interesting because the tuning that results from $T_a = 1$ (figure 3.12) and the uncompensated speed gain is theoretically stable for the closed loop without recycle but not for closed loop with recycle. The theoretically lower bound for T_a in the closed loop without recycle is zero but here it is found that for the closed loop with recycle this lower bound is no longer zero. In order to prove this statement a numerically approach was taken and the results are shown in the figure 3.13. This figure shows for which values of T_a the closed loop with recycle is marginally stable and this is called ultimate T_a.

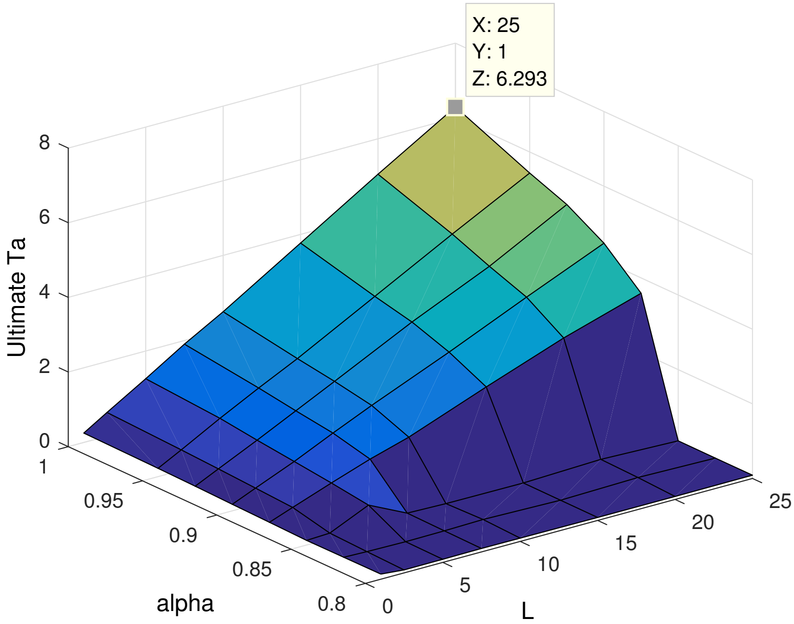


Figure 3.13: Ultimate arrest time for the closed loop process with recycle.

According to figure 3.13 the control engineer can perform the step as it is detailed here without getting an unstable tuning for values of α smaller than 0.8 because for values larger than 0.8 there is a lower bound in the choice of T_a which can result in an unstable controller that theoretically spoken is stable.

Step time > L

The speed gain of the process with recycle is observed and the controller is tuned with the speed gain associated to the process with recycle $k_{v,ult}$. There are three possible choices of the performance parameter.

1. $T_a <$ L
2. $T_a \simeq$ L

3. $T_a > \mathrm{L}$

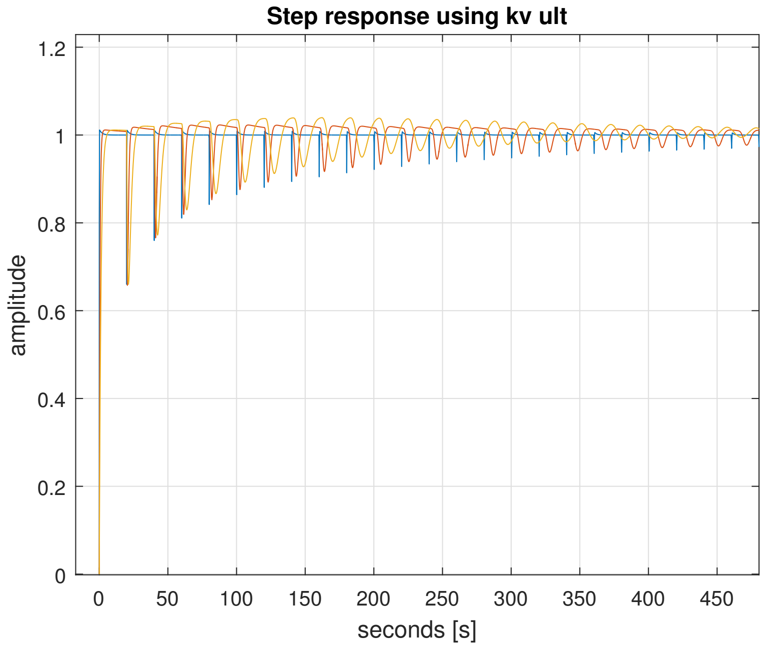


Figure 3.14: Step response closed loop process with recycle for α=0.95, L=20 and T_a=1(blue), 20 (red) and 50 (orange).

A major conclusion that can be extracted from this section is that the step time needs to be at least two times larger than the delay in the recycle to observe with accuracy the both gains of the process. If the speed gain used in the T_a tuning is the speed gain of the process without recycle (k_v) there is a risk for instability as it was explained in the last section. It is important also to mention here that the performance observed is not the expected for a T_a tuning.

On the other hand if the speed gain used is $k_{v,ult}$ there is no risk for instability but the performance observed in the figure 3.14 are not the expected from a T_a tuning. For these reasons a better model that captures more dynamics of the process with recycle is needed and also a tuning method that doesn't demand difficult calculations. In the next section the suggested improvements on model approximation and the corresponding tuning method are explained.

4

Suggested improvements

In the last chapter it is explained how the dynamics of the integrating process change when it is affected by recycle. The recycle affects the dynamics in a way that the integrating process is no longer just an integrator and the tuning methods used in this case are no longer applicable in terms of expected performance (see figure 17 and 19). For this reason the logical step here is to find a model that fits better to the integrating process with recycle and a tuning method for such a model.

4.1 IPZ model approximation

The IPZ model means that the model has an integrating term, a pole and a zero. This model can also be seen as a first order Padè approximation of the recycle term. IPZ model can be described by three parameters $k_{v,m}$, T_1 and T_2.

$$\hat{P}(s) = \frac{k_{v,m}}{s} \frac{(1 + sT_1)}{(1 + sT_2)} \tag{4.1}$$

A common way in industry to estimate the parameters is from a step response. Here it is assumed that A is the magnitude of the control signal step, C is the slope of the step response of the process after the time delay (L) and both asymptotes crosses in the point (t_0,y_0).

According to this

$$k_{v,m} = \frac{C}{A} = (1-\alpha)k_v \tag{4.2}$$

with A = 1 (step size) and C = (1-α) k_v (the slope of the asymptote after L)

$$T_1 = \frac{y_0}{k_{v,m}A} = \frac{k_v L}{k_v(1-\alpha)} = \frac{L}{(1-\alpha)} \tag{4.3}$$

and finally

$$T_2 = t_0 = L \tag{4.4}$$

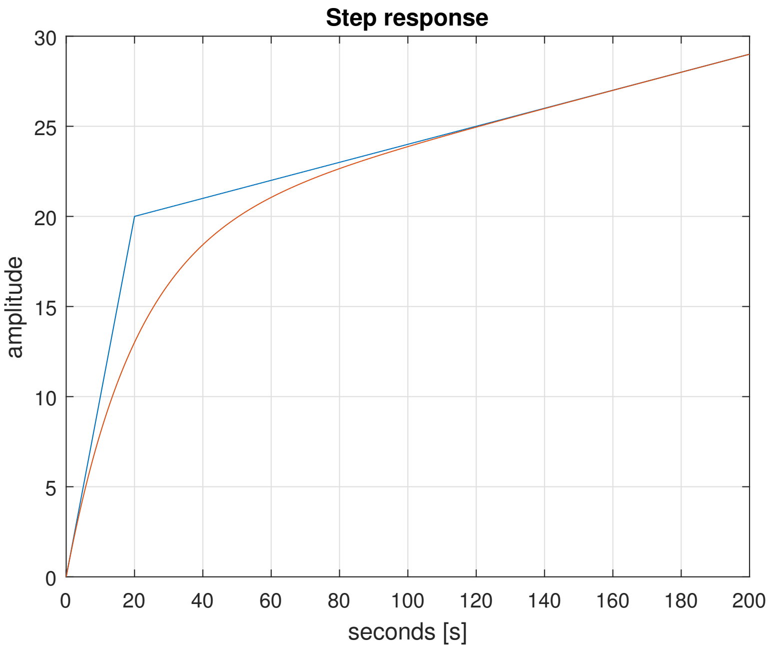


Figure 4.1: Step response of the real process and the approximation with IPZ for k_v=1, α=0.5 and L=20.

There are several advantages of this model approximation:

- The result of this approximation captures more dynamics than using the integrating process by itself.
- Only knowing the k_v, α and L the model can be calculated. This means that knowing the recycle dynamics the approximation of how the model behaves with recycle can be calculated.
- Easy to use.

4.2 Tuning of the IPZ model

There are several methods for tuning of the IPZ model. For simplicity the method recommended in [Forsman, 2005] based on the paper of [Nelson and Gardner, 1996] it is used in which it is recommended to use

$$T_i = T_2 \tag{4.5}$$

and it is stated that the K_c can be chosen by "trial-and-error". This gives a very large range of K_c that can be chosen and one goal of this project is to find a simple tuning method for the integrating process with recycle.

The value of K_c is related with the disturbance rejection as it is suggested in [Skogestad and Grimholt, 2011]. For a disturbance of Δd_0 the controller needs to counteract this effect with a control signal of the same magnitude but with different sign $\Delta u_0 = -\Delta d_0$. Using the formula of the P-controller we get that the smallest $K_{c,min}$ needed to reject the disturbance is

$$|K_{c,min}| = \frac{|\Delta u_0|}{|\Delta y_{0max}|}$$

where Δy_{0max} = the maximum allowed control error.

The possible values of K_c according to the maximum deviation allowed in the output are

$$|K_{c,min}| < |K_c|$$

It is important to mention that this method provide a easy tuning method that doesn't require extensive calculation and gives the most robust solution for a PI controller as it is explained in the following sections.

Why the $T_i = T_2$ is a good choice ?

This means that $T_i = L$ and as it is shown in the figure 4.2 the open loop gain for the integrating process without recycle (PC) gets almost maximum phase margin (around -90°) before the first peak appears when $\omega = acos(\frac{\alpha}{L})$ (see details in appendix A). It is very important that for the uncertainty region the phase margin of open loop gain without recycle (PC) is around -90 ° because the lag that can be introduced by the recycle can vary in values between $-90 < \varphi_{(1-H)} < 90$ for $0 < \alpha < 1$. It is important to mention here that the value chosen for the $\varphi_{(1-H)}$ in our phase calculations is always the lower bound since some relative error can appear when the recycle delay (L) is estimated.

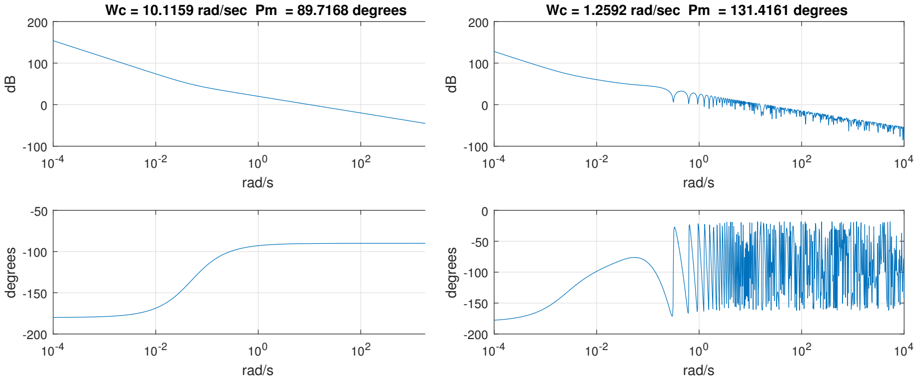
This choice of T_i secures that our controller is going to be stable for all L and $0 < \alpha < 1$.

4.3 Some examples

In this section two examples are presented. The first one tries to show how the tuning method and the model works for common values of α and the second one is a very unrealistic value of α but this is just to show how the tuning method and the model behave in a very extreme case.

Example 1

In this example the following model parameters are used k_v=1, $\alpha = 0.5$ and L=2. The corresponding IPZ model parameters are $T_2 = 2, T_1 = \frac{2}{0.5} = 4$ and $k_{v,m} = (1-\alpha)k_v = 0.5$. This gives $T_i = 2$



(a) Bode plot for PC. (b) Bode plot for PC(1-H).

Figure 4.2: Comparison of the Bode plots for the open loop without recycle (a) and with recycle (b).

and the K_c depends on how much the control engineer allows the output to deviate. For Δy_{0max}= 0.1 and an unit step disturbance the minimum value for the controller gain is $K_{c,min}$=10. The possible tuning choices for the control engineer are all the values of K_c larger than $K_{c,min}$. Let's take a look on the performance K_c=$K_{c,min}$.

1. Step response and disturbance rejection.

   As it is observed in the figure 4.3 the model and the process with recycle have almost the same overshoot and settling time. The peaks that are observed in the figure 4.3 represent the recycle coming back to the system periodically. This effect can not be captured in the IPZ model but it gives a good approximation of the behaviour of the process with recycle.

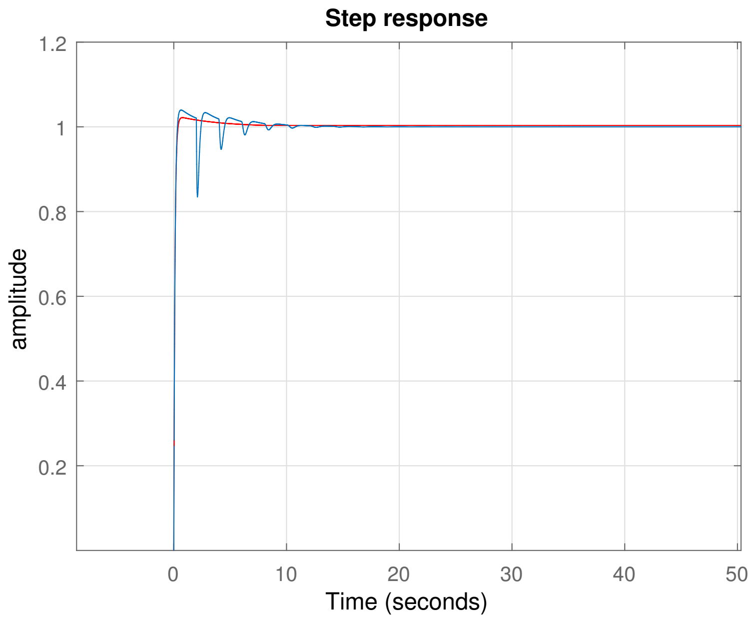


Figure 4.3: Step response r-y for $\hat{P}$C and PC(1-H) with IPZ tuning for K_c=10.

As it was intended the deviation of the output stays between the values calculated in the tuning part (see figure 4.4). In this figure is also observed that the recycle peaks come periodically and that the IPZ model can't capture them.

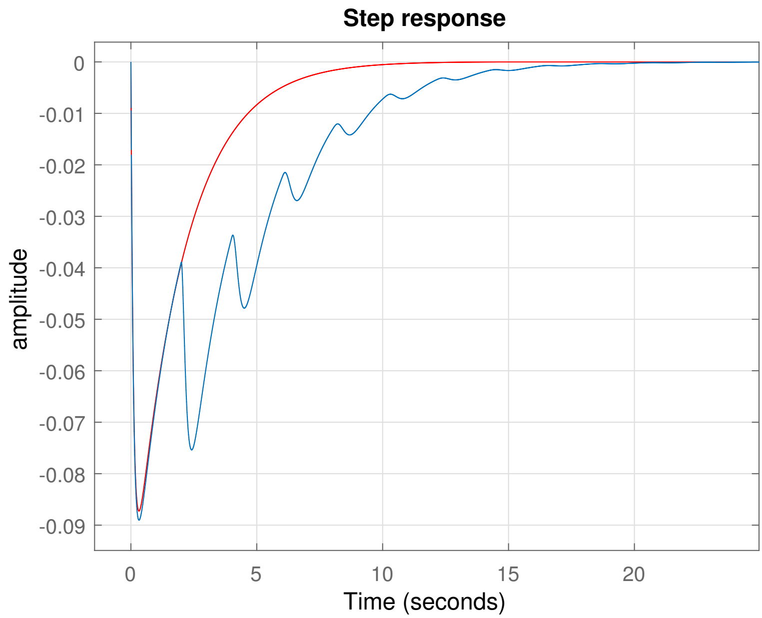


Figure 4.4: Step response d-y for $\hat{P}$C (red) and PC(1-H) (blue) with IPZ tuning for K_c=10.

2. Comparison between IPZ tuning and an "equivalent" T_a tuning with $k_{v,ult}$

   To illustrate the pros and cons of both methods a step response r-y and d-y are displayed. The T_a value for sakes of comparison is a value that gives the same K_c as the one obtained for the IPZ tuning. The T_a tuning used here is the case when the controller is tuned according to the ultimate gain $k_{v,ult}$. The $\hat{P}$ in the following figures represents the integrating process with the ultimate gain as speed gain.

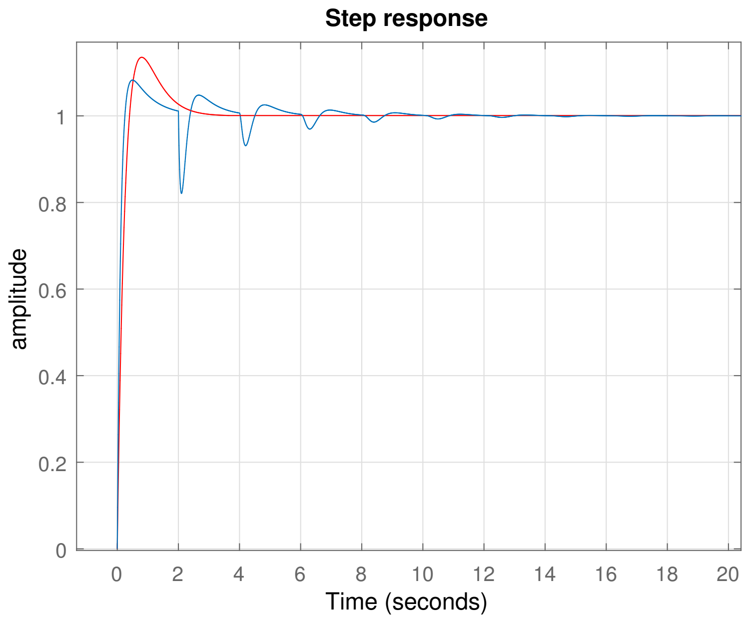


Figure 4.5: Step response r-y for T_a=0.4, α=0.5 and L=2. For $\hat{P}$C (red) and PC(1-H) (blue).

Comparing figure 4.3 and 4.5 one can affirm that both tuning methods have similar performance in terms of settling time but the IPZ tuning has smoother reference following. One advantage is that the IPZ model behaves almost as the plant in terms overshoot and settling time. This can help the control engineer in the "trial-and-error" stage because the control engineer doesn't need to test the values in the process directly and can use some simulation tools.

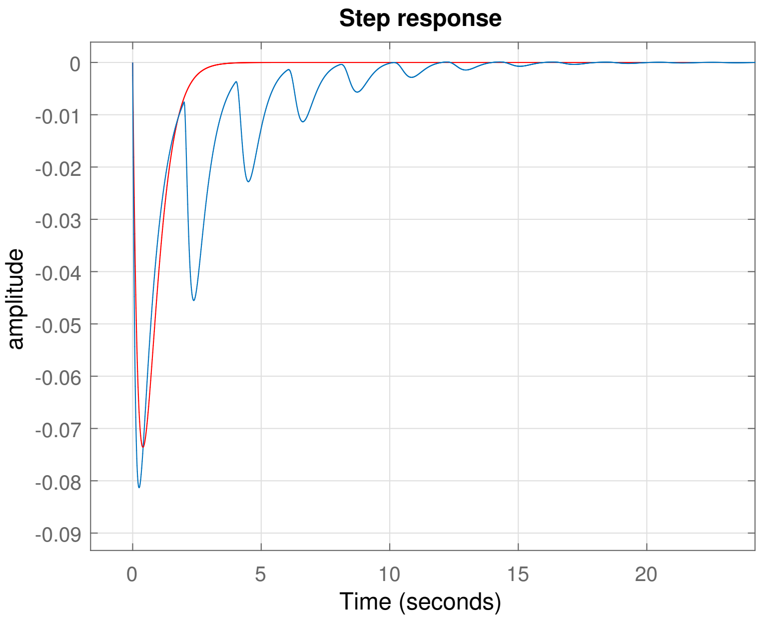


Figure 4.6: Step response d-y for T_a=0.4, α=0.5 and L=2. For $\hat{P}$C (red) and PC(1-H) (blue). In this figure the $\hat{P}$ is the integrating process with $k_{v,ult}$.

Another drawback with the T_a tuning is that the performance observed is completely unexpected for this kind of tuning and process. This is very understandable because the model used to tune the controller doesn't take care of the whole dynamics of the process because one has to choose between the k_v and the $k_{v,ult}$ to use in the T_a tuning. In both choices certain dynamics of the process are ignored. On the other hand as can be observed in figure 4.6 the IPZ is a better approximation and gives a more realistic view of the performance of the process in terms of disturbance rejection, overshoot and settling time.

In figure 4.6 it can be observed that the amplitude of the disturbance is always larger than the case in which the model is used. This implies that the model can not be used to anticipate the largest peak. However in the case in which the IPZ tuning is used (see figure 4.4) the largest peak has the same amplitude as the model. This happens as long as α doesn't take very extreme and unrealistic values (see next section).

Example 2

In this example the following model parameters are used k_v=1, $\alpha = 0.95$ and L=20. This is a very unrealistic choice of α but the goal here is to show that the IPZ tuning method gives stable controller parameters and acceptable step response even with extreme choices of α. The corresponding IPZ model parameters are $T_2 = 20, T_1 = \frac{20}{0.05} = 400$ and $k_{v,m} = (1-\alpha)k_v = 0.05$. The choice of K_c depends on how much the control engineer allows the output to deviate. Let's take the same deviation in the output as the example 1. If Δy_{0max}= 0.1 and disturbance is a unit step. This means that the $K_{c,min} = 10$. The possible tuning choices are as it is explained earlier all the values of K_c larger than $K_{c,min}$. Let's take a look of the performance for the lower bound of the controller gain K_c=$K_{c,min}$ and T_i=T_2.

1. Reference following and disturbance rejection

   In this section $\hat{P}$ is the IPZ model and P is the original integrating process. As figure 4.7 shows the reference following is very smooth and without overshoot. The biggest advantage is that the IPZ model has the same step response as the process with recycle. It helps that the recycle delay is a almost 20 times larger than the settling time (compare with figure 4.3 in which the recycle delay is little bit shorter than the settling time).

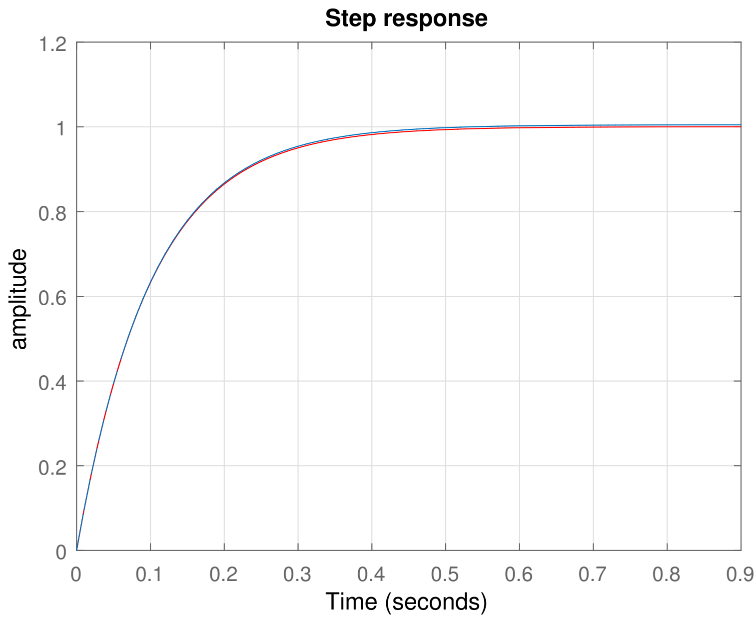


Figure 4.7: Step response r-y for $\hat{P}$C and PC(1-H) with IPZ tuning for K_c=10.

In figure 4.8 it can be observed that the disturbance is also recycled. This makes the deviation of the output larger than the value used in our calculations. Another problem is when the disturbance and the recycled step in the reference comes at the same time. In both cases the deviation is going to be larger than Δy_{0min} but still in a range that can be considered acceptable. In figure 4.8 the output is around 0.04 larger than the maximal deviation allowed in the output.

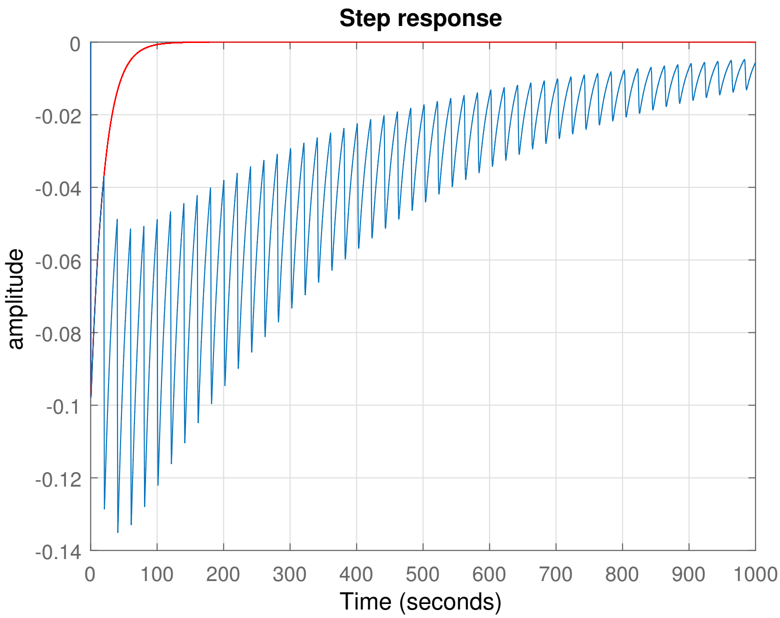


Figure 4.8: Step response d-y for $\hat{P}$C and PC(1-H) with IPZ tuning for K_c=10.

A possible solution could be to increase K_c in order to minimize these two effects introduced by the recycle. A rule of thumb could be to choose a K_c that is two times larger than $K_{c,min}$ so it can be sure that the effect introduced by recycle can not make the output deviate more than the limit imposed in our calculations. It is important to mention here that this only happens for very large and unrealistic values of α.

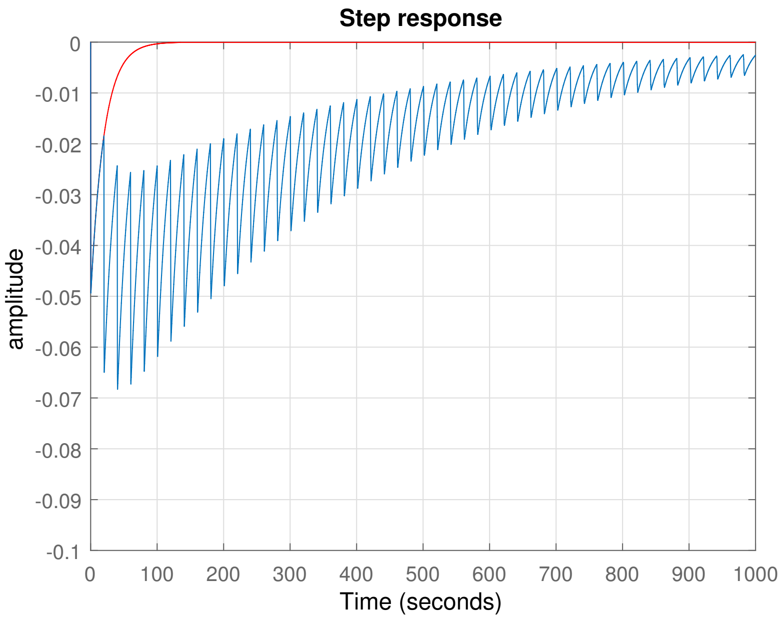


Figure 4.9: Step response d-y for $\hat{P}$C and PC(1-H) with IPZ tuning for K_c=2 $K_{c,min}$.

2. Comparison between IPZ tuning and an "equivalent" arrest-time tuning with $k_{v,ult}$

   As in the preceding example the T_a value is chosen to give the same value of K_c as in the IPZ tuning.

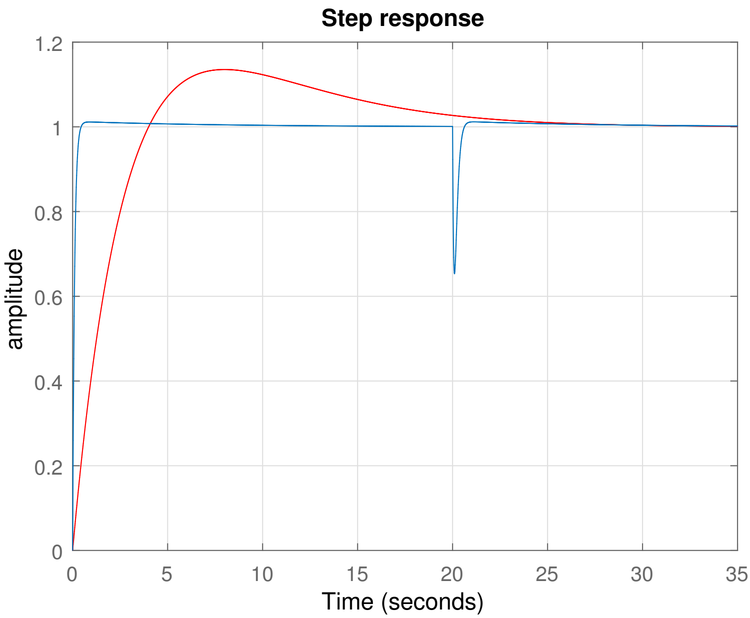


Figure 4.10: Comparasion of the step response r-y in the IPZ tuning and the arrest time tuning for T_a=4, α=0.95 and L=20.

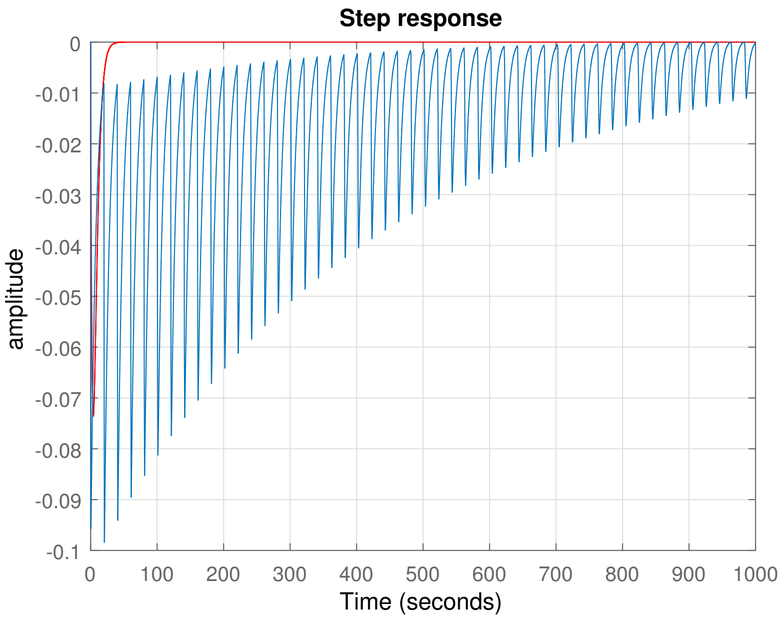


Figure 4.11: Step response d-y for $\hat{P}$C (red) and PC(1-H) (blue) with T_a=4, α=0.95 and L=20.

4.4 Is the IPZ tuning robust for the integrating process with recycle?

As it is explained in section 4.2 this solution gets almost the largest phase margin that a PI controller can get with this type of recycle. To clarify even more this point the maximum theoretical phase margin and the obtained from the process affected by recycle with the IPZ tuning are compared using the same model parameters as in the two preceding examples.

Example 1

For k_v=1, α=0.5, L=2 and the same controller parameters as in last section. The theoretical maximum phase margin for a PI taking in to account the uncertainty in the estimation of the recycle parameters is

$$\varphi_{max,PC(1-H)} = 180 + \varphi_{max,PC} - \varphi_{max,(1-H)} =$$
$$= 180 - 90 - \frac{180}{\pi} atan(\frac{0.5}{\sqrt{1-0.5^2}}) = 180 - 90 - 30 = 60° \quad (4.6)$$

And for the IPZ tuning is 57.4 ° as it is displayed in the figure 4.12.

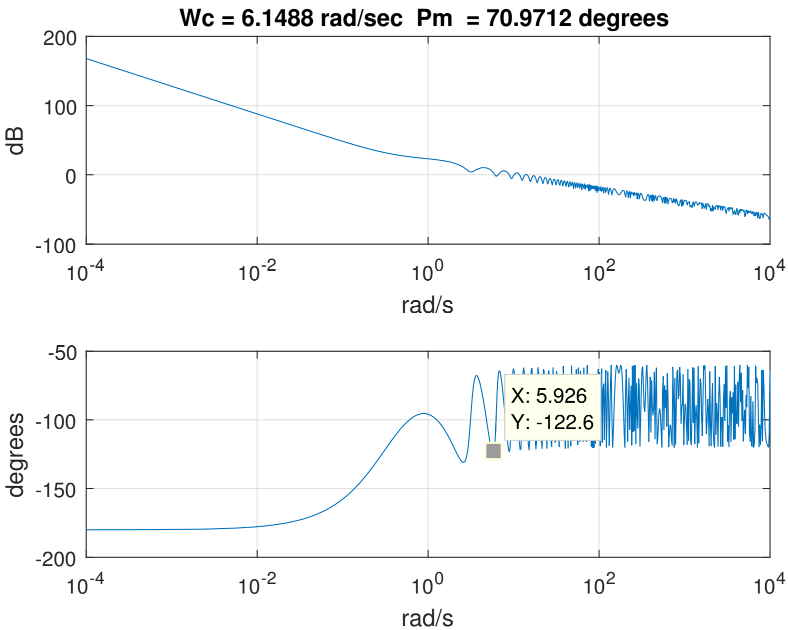


Figure 4.12: Bode plot of PC(1-H) with IPZ tuning.

Example 2

For k_v=1 , α = 0.95, L=2 and the same controller parameters as in example 2. The theoretical maximum phase margin for a PI controller taking care of the uncertainty in the estimation of the recycle parameters is

$$
\begin{aligned}
\varphi_{max,PC(1-H)} &= 180 + \varphi_{max,PC} - \varphi_{max,(1-H)} = \\
&= 180 - 90 - \frac{180}{\pi} atan(\frac{0.95}{\sqrt{1-0.95^2}}) = 180 - 90 - 71.80 = \\
&= 18.2°
\end{aligned}
\tag{4.7}
$$

and the phase margin obtained is 16.4 ° as it can be observed in the following figure.

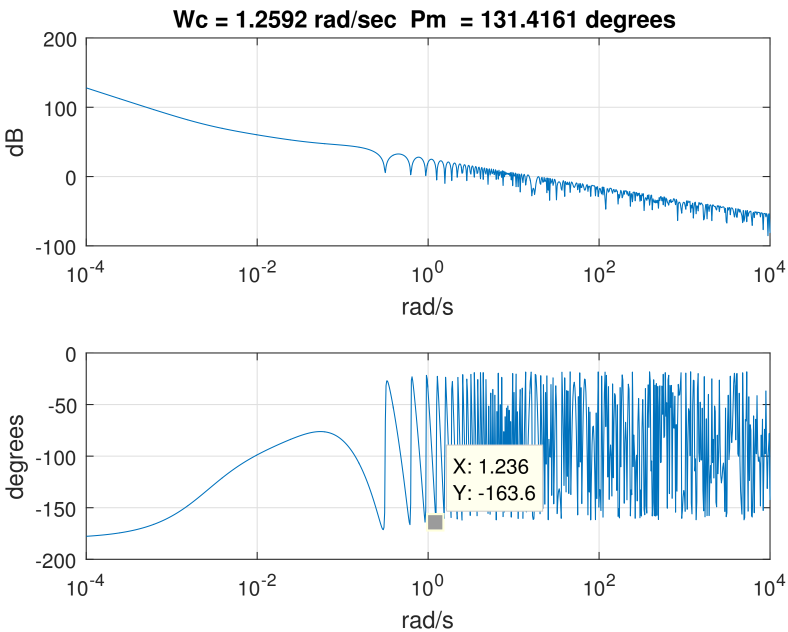


Figure 4.13: Bode plot of PC(1-H) with IPZ tuning K_c=10.

To finish our example, about how robust is the IPZ tuning in the very extreme case, a Nyquist plot is displayed below these lines. The Nyquist plot (figure 4.14) shows that the open loop without recycle has a M_s of 1 and the recycle as it has been calculated (see section B) can only introduce a phase lag smaller than 90 degrees. This means that the controller can not be unstable. In this extreme value of α the M_s is large but is the best M_s that can be obtained for a PI controller with an integrating process affected by recycle.

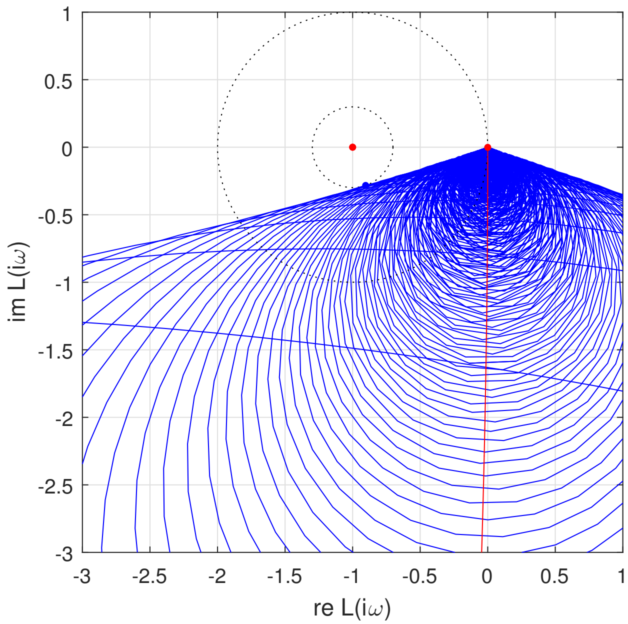


Figure 4.14: Nyquist of PC(1-H) (blue) and PC (red) with IPZ tuning with M_s=3.35 and M_s=1 respectively.

4.5 Conclusions

There are several conclusions that can be extracted from this report:

1. Step time: The step time length should be at least two times longer than the time delay in the recycle. Otherwise the step doesn't capture all the dynamics of the process with recycle and just the dynamics without recycle are observed.

2. Tuning methods for integrating process (T_a tuning) should not be used for the integrating process with recycle. The tuning can result in a stable close loop step response but the performance observed is totally unexpected for a T_a tuning.

3. The IPZ model is a better approximation of the integrating process with recycle.

4. The IPZ tuning method detailed here is easy to use and gives the most robust solution for a PI controller.

5. The IPZ model has the disadvantage that it does not capture the recycle peaks in the simulation of the step response. To capture these recycle peaks a more complicated model is needed (e.g. a 7th order Padè approximation of the recycle term). This model can require a very complicated tuning method and results in a very small improvement in comparison with the method suggested here.

A

Maximum phase lag calculations

The phase of 1-H is given by

$$\varphi_{(1-H)} = arg(1 - \alpha e^{-sL}) = atan(\frac{\alpha sin(\omega L)}{1 - \alpha cos(\omega L)}) \tag{A.1}$$

The maximum is obtained when

$$\frac{d\varphi_{(1-H)}}{d\omega} = \frac{L\alpha(cos(\omega L) - \alpha)}{1 - 2\alpha cos(\omega L) + \alpha^2} = 0 \tag{A.2}$$

so that

$$cos(\omega L) = \alpha \tag{A.3}$$

and solving for ω_{max}

$$\omega_{max} = acos(\frac{\alpha}{L}) \tag{A.4}$$

Substituting the equation 38 in 35 we get

$$\varphi_{max,(1-H)} = atan(\frac{\alpha}{\sqrt{1 - \alpha^2}}) \tag{A.5}$$

B

Boundaries analysis of the recycle term

B.1 Amplitude

$$\begin{aligned} |1{-}\alpha\ \mathrm{e}^{-sL}| &= \sqrt{1-\alpha(cos(\omega L)-jsen(\omega L))} = \\ &= \sqrt{1-2\alpha cos(\omega L)+\alpha^2} \end{aligned} \tag{B.1}$$

This expression has its maximum when ωL is equal to (2n+1)π where n = 0,1,2,...

$$max|1-H| = 1+\alpha \tag{B.2}$$

and its minimum when ωL is equal to 2nπ for the same n

$$min|1-H| = 1-\alpha \tag{B.3}$$

B.2 Phase

As it has been shown in the appendix A the maximum value of the phase of 1-H is given by the following formula

$$\varphi_{max,(1-H)} = atan(\frac{\alpha}{\sqrt{1-\alpha^2}}) \tag{B.4}$$

if $0 < \alpha < 1$

$$-90^\circ < \varphi_{max,(1-H)} < 90^\circ \tag{B.5}$$

Bibliography

Denn, M. and R. Lavie (1982). “Dynamics of plants with recycle”. *The Chemical Engineering Journal* **24**:1, pp. 55–59.

Forsman, K. (2005). *Reglerteknik för processindustrin.* Studentlitteratur. ISBN: 9144037899.

Forsman, K. (2015). “Useful formulas”. *Perstorp AB internal site.*

Luyben, W. L. (1993a). “Dynamics and control of recycle systems. 1. simple open-loop and closed-loop systems”. *Ind. Eng. Chem. Res., 1993, 32 (3), pp 466–475.*

Luyben, W. L. (1993b). “Dynamics and control of recycle systems. 2. comparison of alternative process designs”. *Ind. Eng. Chem. Res., 1993, 32 (3), pp 476–486.*

Luyben, W. L. (1993c). “Dynamics and control of recycle systems. 3. alternative process designs in a ternary system”. *Ind. Eng. Chem. Res., 1993, 32 (6), pp 1142–1153.*

Luyben, W. L. and B. D. Tyreus (1993). “Dynamics and control of recycle systems. 4. ternary systems with one or two recycle streams”. *Ind. Eng. Chem. Res., 1993, 32 (6), pp 1154–1162.*

Morud, J. and S. Skogestad (1996). “Dynamic behaviour of integrated plants”. *J Proc. Cont. Vol. 6, No. 2/3, pp. 145-156.*

Nelson, D. and T. Gardner (1996). “Optimizing paper machine dryer control- a case of study”. *Pulp Paper Canada 97:11, pp.43-49.*

Scali, B. and R. Antonelli (1996). "Performance of different regulators for plants with recycle". *Computers chem. Engng, 19 (1995), pp. S409–S414*.

Skogestad, S. and C. Grimholt (2011). "The simc method for smooth pid controller tuning". *PID Control in the Third Millennium, R. Vilanova, A. Visioli . Chapter 5*.

Taiwo, O. and V. Krebs (1996). "Robust control system design for plants with recycle". *Chem. Eng. J., 61 (1996), pp. 1–6*.

Lund University
Department of Automatic Control
Box 118
SE-221 00 Lund Sweden

Document name
MASTER´S THESIS

Date of issue
June 2016

Document Number
ISRN LUTFD2/TFRT--6007--SE

Author(s)
Santiago Castro Chans

Supervisor
Mohammed Adlouni, Perstorp AB
Richard Pates, Dept. of Automatic Control, Lund University, Sweden
Bo Bernhardsson, Dept. of Automatic Control, Lund University, Sweden (examiner)

Sponsoring organization

Title and subtitle
Control and properties of processes with recycle dynamics

Abstract

This project discusses the effects of recycle streams on the dynamics and performance of chemical plants. The questions addressed are: can the current industry standard tuning methods still be applied to systems with recycle, and if not, how can they be modified? This is approached by analysing the arrest time tuning method when applied to an integrating process with and without recycle. The results show that the integrating model does not capture all the relevant dynamics of the integrating process with recycle. Consequently a new model, and an easy tuning method for the industry standard controllers, is proposed.

Keywords

Classification system and/or index terms (if any)

Supplementary bibliographical information

ISSN and key title
0280-5316

ISBN

Language
English

Number of pages
1-52

Recipient's notes

Security classification

http://www.control.lth.se/publications/