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Process Control & Automation of a Batch Reactor

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By

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DECLARATION

I, the undersigned, declare that this report is entirely my own written work, except where otherwise accredited, and that it has not been submitted for a degree or other award to any other university or institution.

Signed: ______________________________

Date: _________________

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Abstract

The ambition for this project was to develop a split range PID controller with SCADA screens to facilitate manual and automatic control of a pilot plant scale batch reactor. Since the characteristics of the system were unknown a step response was obtained from the system and from the experimental results a model of the system was developed and analysed.

The PID controller for the system was implemented via an Allen Bradley MicroLogix 1100 Programmable Logic Controller with the human interface for the controller being a SCADA system that was developed using the software package LabVIEW a visual programming language. From the experimental results two models of the system were developed using Simulink a graphical multi domain simulation package. PID controllers were developed for both models using various tuning methods including the Ziegler-Nichols tuning rules; an industry standard method of tuning a PID controller and through rigorous testing and development the controller that produced the best system response was chosen and implemented as the controller for the system.

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1. Introduction

1.1 Background

This project is concerned with the temperature control of a pilot scale batch reactor. Batch Reactors are utilised in several industries including the pharmaceutical industry to produce medicines. For most drugs to reach the market place they have to be FDA approved and for a company to receive FDA approval the manufacturing process of their products must adhere to strict tolerances, one of those parameters that must adhere to strict tolerances during the production of a batch being temperature.

The temperature of the medicines during the different stages of the production process is of critical importance. In industry the temperature of a batch reactor is usually controlled manually before switching to automatic control at a later stage of the process. To successfully regulate the temperature of the reactor a facility for both manual and automatic control must therefore be installed. The reason automatic control must be used is that it is not viable on a mass scale to control the temperature of a batch process manually for the duration of the process which in some instances may take days [1], therefore the production process must be capable of self-regulation during certain stages of the process. The reason manual control is needed is that in industry the automatic temperature control of a closed batch is extremely difficult due to the long dead times and time constants that form the system characteristics, these characteristics do not complement the conventional PID controller and also reduce the system's stability margin [2].

One type of controller that has been developed to overcome some of the shortcomings of PID controllers is the Model Predictive Controller (MPC). For the temperature control of a batch reactor the MPC improves on the performance of the PID controller by reducing the process time and minimising the error between the Process Variable (PV) and the Set Point (SP) [3], an error which in the production of medicines could lead to a deviation from the approved process and therefore a ruined batch resulting in reduced productivity and increased production costs. The major issue with using model predictive controllers is the huge computational capacity required to implement the controller, this is due to the control algorithm, an on-line computational quadratic problem which in some instances requires a stand-alone computer to run, an off-putting factor when considering this controller.

It is important to note that due to the nature of batch processes the hardware used in the manufacturing process will not change but the software will, this is where the controller interfaced with a SCADA system becomes invaluable as specialised programmes can be remotely programmed to the controller in the production of different products, meaning that space and equipment can be utilised to their maximum as the need to change locations in the manufacture of different products ceases.

With the PID controller's dominant place in industry [4] it is essential for aspiring and practising control and automation engineers to be thoroughly versed in the theoretical and practical applications of the PID controller, this allied with the PID controller's suitability for low order systems [5], the working knowledge engineers have and the accessibility and resources available will in the author's opinion make the PID controller an essential tool in the process industries for years to come.

1.2 Goals

- Investigate different system identification techniques.
- Derive a First Order Plus Dead (FOPDT) Time system.
- Derive a Second Order Plus Dead Time (SOPDT) model of the system.
- Develop system models using the software packages Matlab and Simulink.
- Implement a Cascaded master/slave control architecture.
- Develop a well-tuned control algorithm.
- Investigate the performance of single system controller versus a system utilising a cascaded controller architecture.
- Investigate the different methods of controller design.
- Investigate the effects of system disturbances and the effect the plant's characteristics have on the system's disturbance rejection performance.
- Learn how to programme using an Allen Bradley MicroLogix 1100 Programmable Logic Controller.
- Implement the developed control algorithm in discrete form to a PLC via the software package RSLogix Micro English.
- Employ Split Range control to control the pilot scale plant.
- Learn how to use the software package LabVIEW.
- Develop Graphical User Interface screens to enable Supervisory Control And Data Acquisition (SCADA) of the process.
- Ultimately successfully control the process through a GUI.

1.3 Issues

- The room where the Batch Reactor is situated is also used for laboratories resulting in limited access to the room and therefore limited access to the Batch Reactor.
- The OPC package available is a demo version and has a two hour time limit whereas the Batch Reactor has a time constant of over two hours.
- There are other students undertaking projects on the same pilot scale Batch Reactor further reducing access to the plant.
- I am majoring in Power engineering and as a result this project will be particularly challenging.

1.4 Thesis Chapter Descriptor

Chapter 1 Introduction: Chapter 1 presents the reader with an overview of the Batch Reactor and the challenge in controlling the temperature during the process. The PID controller and its importance to industry are discussed and the Model Predictive Controller is presented to the reader as an alternative form of controller to the PID controller. The goals and issues relevant to this project are also listed.

Chapter 2 Literature Review: Chapter 2 delivers to the reader the pre-requisite material to this project. The material delivered to the reader is in this section was developed through the study of research papers, industry guides and journals that concern PLCs, PID, and Batch and Chemical Reactors. Much of the information on control systems originates from undergraduate and postgraduate control engineering textbooks and also class notes from control systems modules available in Dublin Institute of Technology.

Chapter 3 Methodology: In Chapter 3 the complete process in undertaking this project is detailed from initial analysis of the plant to the method of translating the developed controller from continuous form to discrete form.

Chapter 4 System and Control Analysis: Chapter 4 details the mathematical process of how the system was derived and examines how a trial and error approach must be adopted in the process of developing the best fit for purpose model. The system is viewed and analysed from a disturbance perspective using block diagram algebra and the process control philosophy is presented to the reader.

Chapter 5 Analysis of Results: In chapter 5 the performance of FOPDT and SOPDT system models employing single and cascaded controller architectures with the controllers designed using various methods are examined. The disturbance rejection performance of the system is analysed and also looked at from the position that the system architecture was structured in a more desirable fashion.

Chapter 6 Conclusion: Chapter 6 summarises the findings from this project and also looks at future work that could be undertaken and possible improvements to the pilot scale plant.

2. Literature Review

2.1 Intro

Control systems is an area of engineering which crosses disciplines, when researching this topic one will find many articles published by mechanical, control and chemical engineers. Many pharmaceutical companies such as Pfizer employ engineers specialising in the aforementioned areas in the design construction, commissioning, operation and maintenance of batch processes, meaning that engineers from different backgrounds must work together to successfully complete projects therefore making this industry a particularly challenging one to work in and one that calls for the engineer to have a broad skill and knowledge base.

2.2 Control Systems

Control systems are either open-loop or closed loop in their structure. In an open loop system as shown in figure 2.1 there is no direct correlation between the input signal i.e. the Set Point (SP) and the output signal i.e. the Process Variable (PV). In an open loop system if a disturbance is introduced to the system then manual manipulation of the SP will be needed, if the strength of the disturbance alternates then continual manipulation of the SP will be needed which may lead to instability, in most processes this is not acceptable. In the case of the Batch Reactor if an open loop system was exclusively utilised in the control of a batch manufacturing process the product would most likely fail to meet the standards defined in that particular industry, this is why feedback and a closed loop system output is essential to most processes.

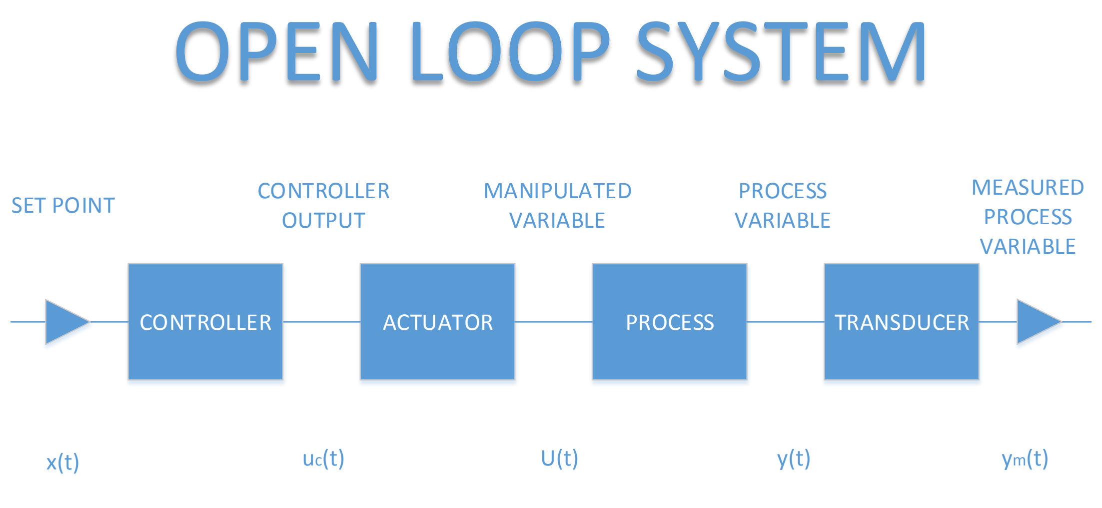


Figure 2. 1 Open Loop System

A closed loop control system employs feedback, with the feedback signal taken from the system output i.e. process variable, this type of system is shown in block diagram form in figure 2.2. In a feedback control system the PV is compared with the SP, the difference between the SP and PV is called the error. With regard to feedback control systems there are two options those being:

1/ Positive feedback: If the designer chooses this option the error will be compounded every-time the PV signal is transmitted to the controller, this will usually lead to system instability.

2/ Negative feedback: If the designer chooses this option the feedback signal is used to reduce the error every-time the PV signal is transmitted back to the controller, this form of feedback facilitates a method of bringing stability to a system.

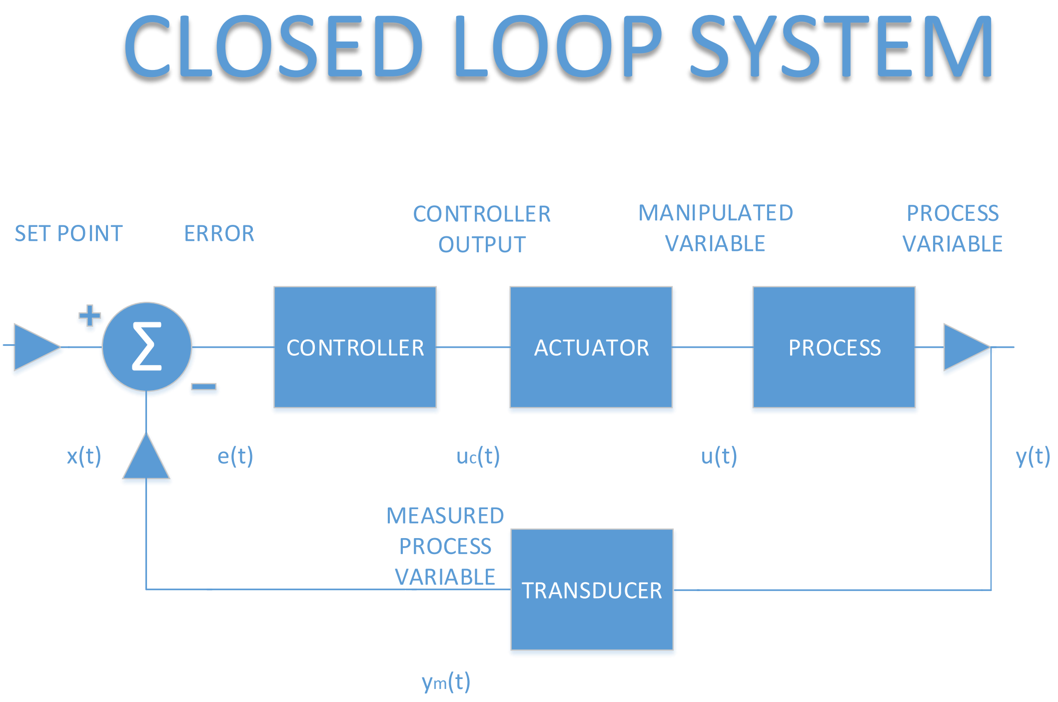


Figure 2. 2 Closed Loop System

2.3 Controller Tuning

An appropriate PID controller algorithm must be developed to control the manufacturing process; many systems are unique and require a custom control algorithm to obtain optimal performance. A controller may be in some cases designed 'online' i.e. while the system is running using a trial and error approach, this is time consuming and potentially extremely costly [6] and dangerous practice that is largely dependent on the skill and knowledge of the engineers and technicians involved.

2.4 System Identification

System identification is the process whereby the characteristics of a system are identified, one of the main system characteristics is the system order with most systems being satisfactorily modelled as either FOPDT or SOPDT [7].

2.4.1 FOPDT System Characteristics

- Dead Time denoted θ_d is the delay between a change in system input and a recognisable change in system output.
- The system gain K is a constant that is defined as the change in output divided by the change in input.
- The time constant τ is an essential characteristic of first order systems, this is the point in time that it takes the output to reach 63.2% of its final change; it takes 5τ for a first order system to reach steady state.

2.4.2 SOPDT System Characteristics

- θ_d is the same as the first order system.
- K is the same as the first order system.
- Zeta (ζ) is a measure of the system's transient response and is the ratio of the actual system's damping to the damping required for a critically damped response, it is generally classified as over damped ($\zeta > 1$), critically damped ($\zeta = 1$) or under damped ($\zeta < 1$).
- Natural frequency (ω_n) is the frequency at which the system would oscillate for a theoretically infinite time if there was no damping in the system i.e. $\zeta = 0$.

2.5 System Modelling

To derive the above mentioned characteristics generally two methods are used those being Mathematical Modelling and Empirical Modelling.

2.5.1 Mathematical Modelling

Control systems may be modelled using a set of differential equations to represent the system dynamics. A mathematical model of a system will not be unique and depends on the interpretation of the engineer or mathematician modelling the system. The differential equations used to model the system dynamics are usually based on physical laws such as Newton's and Kirchhoff's laws [8] with the laws utilised being dependant on the type of system to be modelled e.g. mechanical, electrical etc. Mathematical system models may assume many different forms; those commonly found in control engineering include differential equations, state space equations and transfer functions. One of the major advantages of representing a model of a system with a transfer function is that the systems characteristics such as K, τ etc. are explicitly presented. In mathematical modelling a compromise must be made between simplicity and accuracy, engineers unlike mathematicians will ignore certain system properties to model a system as long as they can still derive a reasonably accurate model of the system.

2.5.2 Empirical Modelling

An empirical model of a system is a model constructed using test data. The test data recorded is usually the system response to an input signal. There are many types of input signal that may be introduced to the system with two favoured forms being the Step Input and the Ramp Input, a Step Input is shown in figure 2.3.

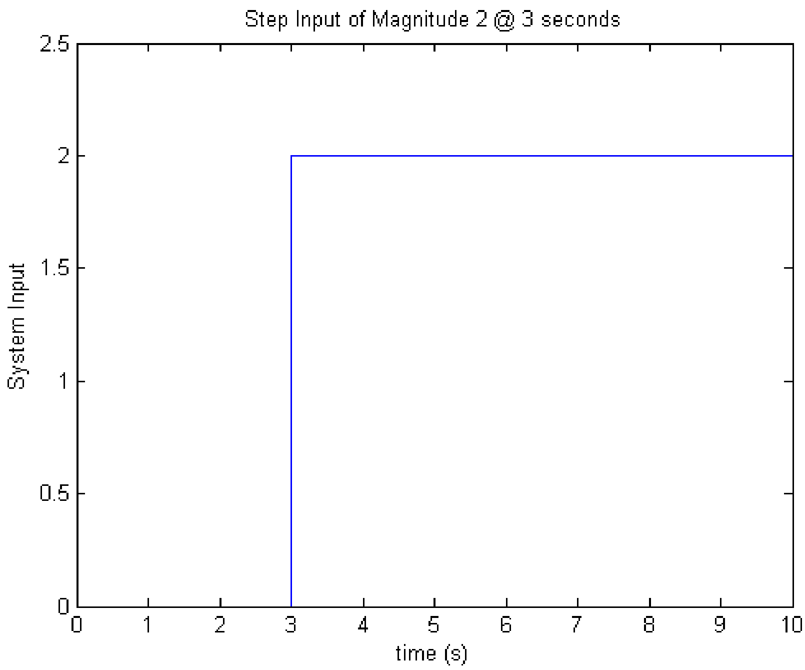


Figure 2. 3 Step Input

The Step Input is a good way of obtaining the transient response and the steady state error [9]. A Step Input is a constant command that increases the input value from an original steady state value to a greater steady state value, a Step Decrease which can be utilised equally effectively decreases from an original steady state value to a lower steady state value. Usually the input variable the Manipulated Variable MV such as temperature, position, velocity etc. is of the same form as the output Process Variable PV. The ideal Step Input is instantaneous but in reality this is not the case however it may be considered so provided that the time to change from one steady state value to another is significantly smaller than the time for the system output to reach a steady state value. The step test when performed online would most likely prove expensive in many industries, using the pharmaceutical industry as an example during a step test the PV would diverge significantly from the SP for a relatively long period of time and therefore most likely destroy the product.

The Ramp Input

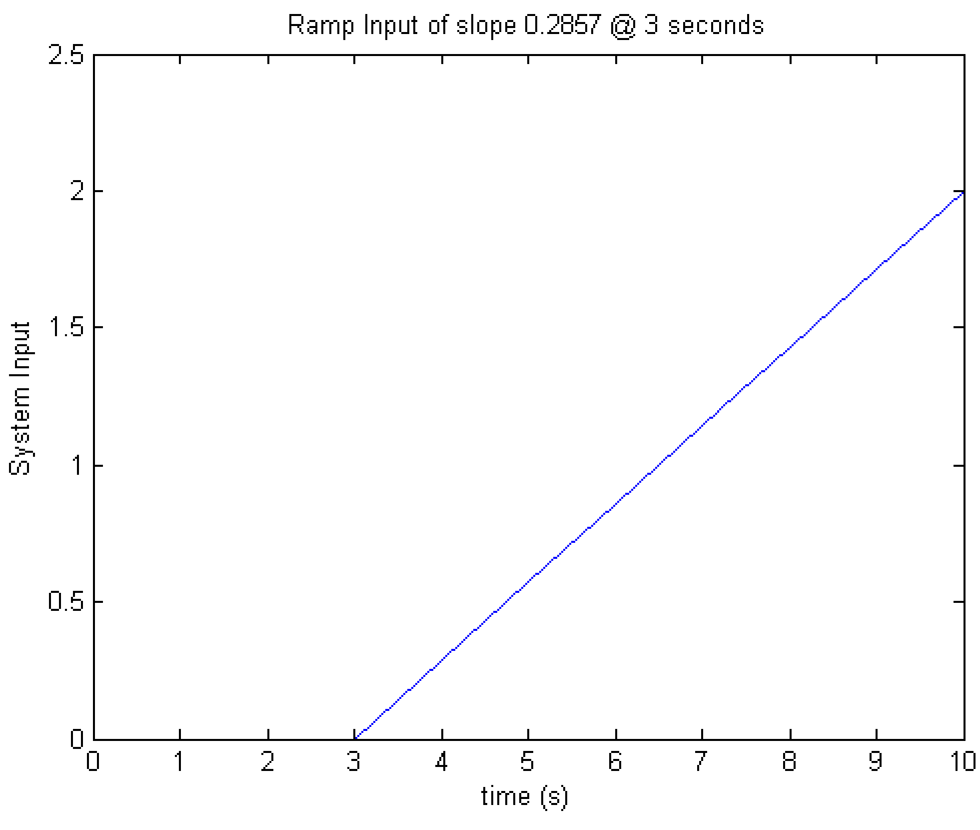


Figure 2. 4 Ramp Input

The Ramp Input is a linearly increasing command and is shown in figure 2.4, whatever the process variable of interest is be it temperature, position, acceleration the ramp represents a linear increase in that variable, the rate of increase is found by calculating the slope of the ramp.

Other input signals used to identify systems include the sinusoid, parabola, impulse, pulse, doublet, pseudo random binary sequences, exponential inputs and noise, the choice of test signal depending on the system to be tested and the knowledge and experience of the engineer.

2.6 Factors affecting the quality of the test data

To construct an accurate model of a system requires the engineer to be mindful of the following points:

Conditions: Process modelling ideally requires that the system is operating in steady state before testing commences however this may not always be possible as sometimes disturbances may be generated intrinsically. When modelling empirically it is essential to acquire quality data to construct an accurate model of the system under test and ultimately design a well-tuned controller [10].

Disturbances: System disturbances can be constant or intermittent depending on the system and the environment the system is situated in. These disturbances can be difficult and sometimes impossible to quantify and can corrupt the test data. If the system tester feels that extrinsic disturbances were introduced to the system during the course of testing the system it would be prudent to carry out a re-test.

Consistency: The test should ideally be repeated at least twice if the test results are to the engineer's satisfaction, if not testing should re-convene until quality consistent data has been collected.

Noise: Most systems especially in industrial environments will be subject to a certain level of noise, one of the characteristics that the quality of the test data is measured against is the noise levels and as a general rule the change in the PV should be between 5 and 10 times the noise level present in the system.

Sampling Frequency: Data should be sampled at a minimum rate of one tenth the time constant found from the Process Reaction Curve if the component of the system under test is first order. If the sampling frequency is too slow the quality of the data will be poor and possibly misleading. A general rule when testing any n^{th} order system where temperature is the Process Variable is to sample at intervals between five and thirty seconds [10] the most appropriate interval being dependant on the dynamic behaviour of the system.

2.7 System models

FOPDT & SOPDT

An empirical model of an unknown system is based on the system output response which for a first order system is known as a Process Reaction Curve (PRC). If the system output response resembles a PRC then a first or second order model of the system may be developed [8] and the system characteristics approximated, these characteristics are now looked at in finer detail.

Dead time

Dead time is a common characteristic of industrial processes which must be accounted for to accurately model a system. Dead time can come from many sources and the amount of dead time is usually down to the type of process and the system in place to control the process. Common areas where dead time may be accounted for include the transfer of energy, the accumulation of multiple time lags for a system containing numerous low order processes in series and the processing time for sensors and controllers [11], both of which may contain computationally heavy algorithms as is the case with Model Predictive Controllers [12]. Fortunately dead time is usually modelled cumulatively and not individually, and in the case of a first order system can be approximated from a PRC. It is very important to remember that the dead time introduces negative characteristics to a system by reducing both the phase and gain margins, both of which make the control of a system more difficult.

Two Point Method

The two point method is a form of system graphical analysis used to construct a FOPDT model of a system in response to a test signal such as a Step Input. When using the two point method the points of interest are the 28% and the 63.2% points of the change in process output, these two points are used to calculate the systems time constant along with the dead-time and the system gain.

Another similar and common form of system graphical analysis is the tangent and point method, the two point method is however a superior method to the tangent and point method [6] as this method is totally dependent on accurately determining the maximum slope of the system response which is prone to error, the two point method is the graphical method of choice and is shown along with this method's corresponding formulae in figure 2.5.

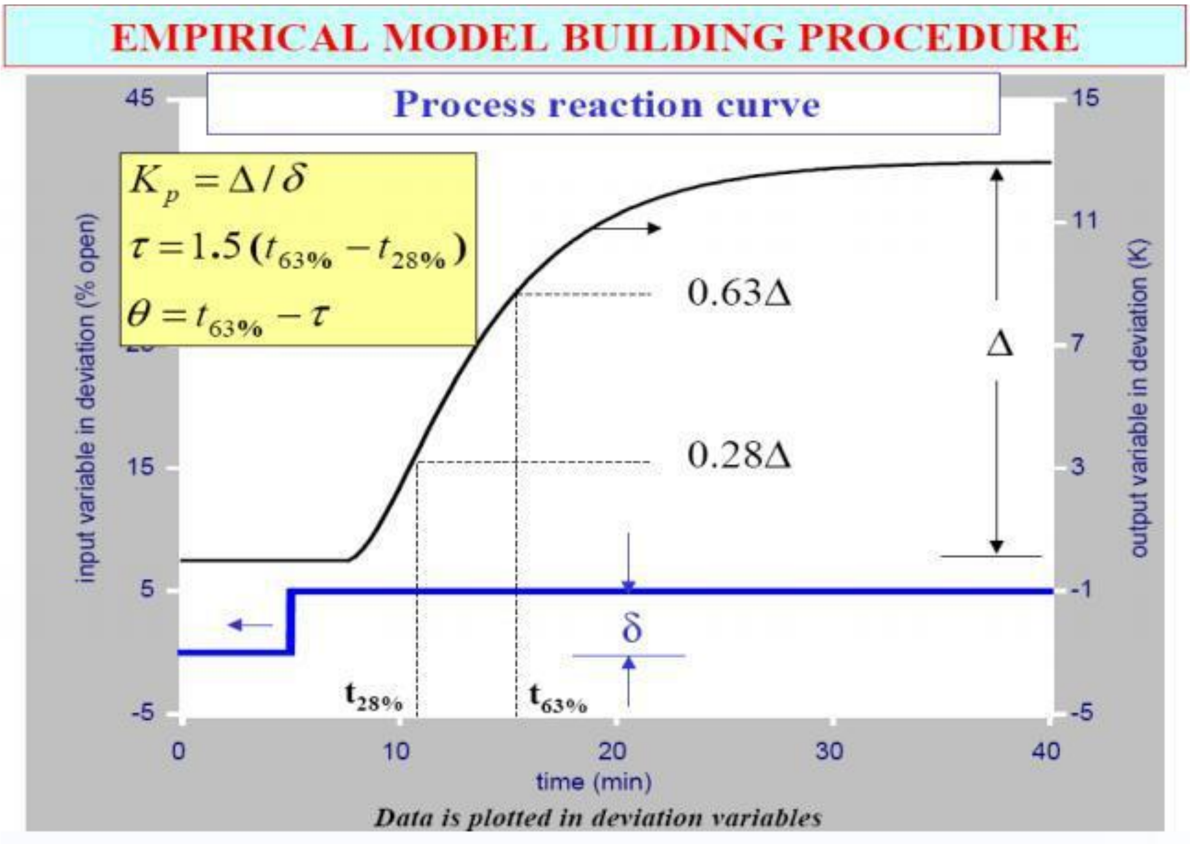


Figure 2. 5 Two Point Method [6]

The FOPDT model is one of the most commonly used models to model an n^{th} order system and takes the form shown in the equation below in Laplace form.

$$G(s) = \frac{K}{\tau s + 1}$$

This system is also shown in block diagram form in both the time domain on the LHS of figure 2.6 and the frequency domain on the RHS of figure 2.6.

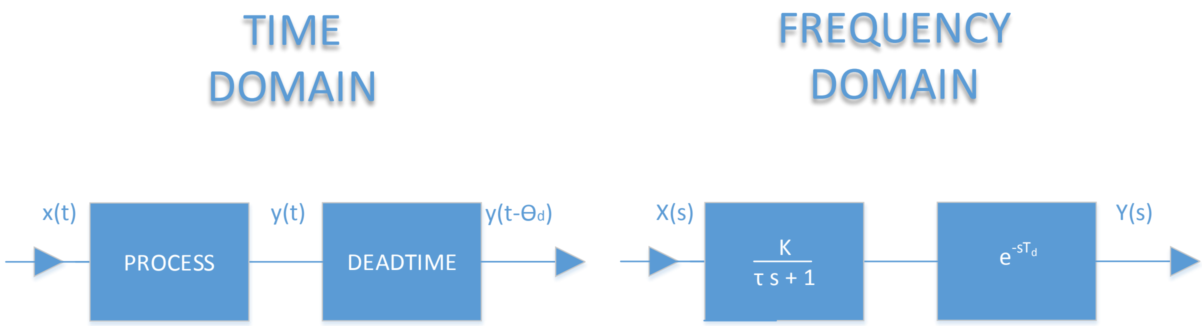


Figure 2. 6 1st Order TF Block Diagram

The subsystems of figure 2.6 can be amalgamated into a single system to produce the transfer function shown in the equation below.

$$G(s) = \frac{Ke^{-sT_d}}{\tau s + 1}$$

While it is convenient to assume that the system under test is first order in practice this is not always the case with the exception being very simple systems, in practice many systems are comprised of multiple subsystems with each subsystem having their own individual characteristics, sometimes if a time constant of one subsystem is relatively small in relation to the other subsystems then this time constant may be incorporated into the model of the system as dead time [13].

SOPDT

A Second Order Plus Dead Time (SOPDT) model of a system may prove more accurate than a FOPDT model and can be derived from a PRC; one method of constructing a SOPDT model of a system is to uses Smith's Method. When using Smith's Method the points of interest of the PRC are the points in time at which the PRC has reached 20% and the 60% of its final steady state value as opposed to the 63.2% point if constructing a FOPDT model. Smith's chart which is shown in figure 2.7 is used to find the damping ratio of the system plus the ratio t_{60}/τ with this ratio used in the derivation of the secondary plant's time constant.

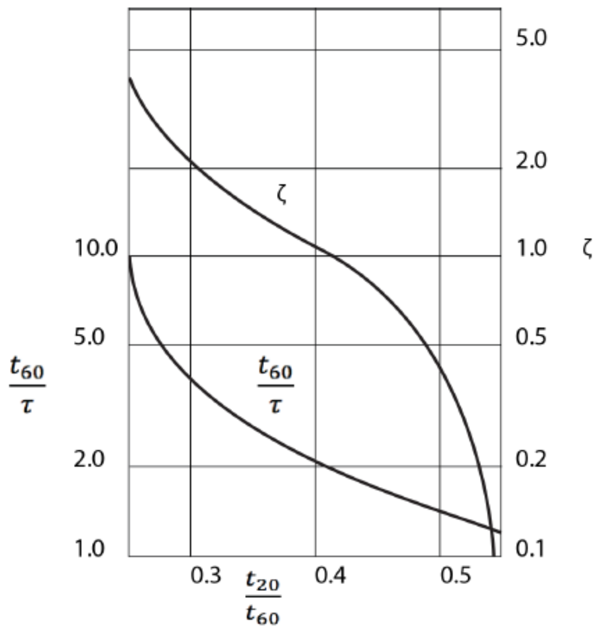


Figure 2. 7 Smith's Method Chart

From using Smiths method an equation of the form $\frac{Ke^{-\theta s}}{\tau^2 s^2 + 2\varsigma\tau s + 1}$ can be derived

This equation may then be represented as $= (\tau_1 s + 1)(\tau_2 s + 1)$ and expanded to $\tau_1\tau_2 s^2 + (\tau_1 + \tau_2)s + 1$

The time constant τ_1 the dominant time constant should be known, therefore by equating the above two equations τ_2 may be found.

Dividing by τ the system transfer function may be expressed in unity constant coefficient form, this is shown in the transfer function below:

$$\frac{K\omega_n{}^2 e^{-\theta_d s}}{s^2 + 2\varsigma\omega_n s + \omega_n{}^2}$$

This model can be used for over-damped and under-damped PRCs but cannot be used for the following two cases:

1. The system response is first order and therefore τ2/τ1=0.
2. The system response is critically damped and therefore τ2/τ1=1.

When using this method any dead-time must be subtracted from the time it takes the output response to reach the 20% and 60% points, it is recommended to visually determine θ_d from the system response however some further refining of θ_d may be required to obtain a satisfactory system model [8].

2.8 System Controllers

The ultimate goal of the control engineer is to design a controller that will drive the error signal to zero, this only occurs when the Process Variable equals the Set Point, to do this a control engineer must develop a controller for a closed loop system, with two prevailing forms of controller being the On/Off controller with Hysteresis and the PID controller.

2.8.1 On/Off Controller with Hysteresis

An example of an On/Off controller with Hysteresis is the thermostat, the thermostat is essentially a switch that forms part of the power circuit from the mains supply to the electrical load, this circuit is shown in figure 2.8.

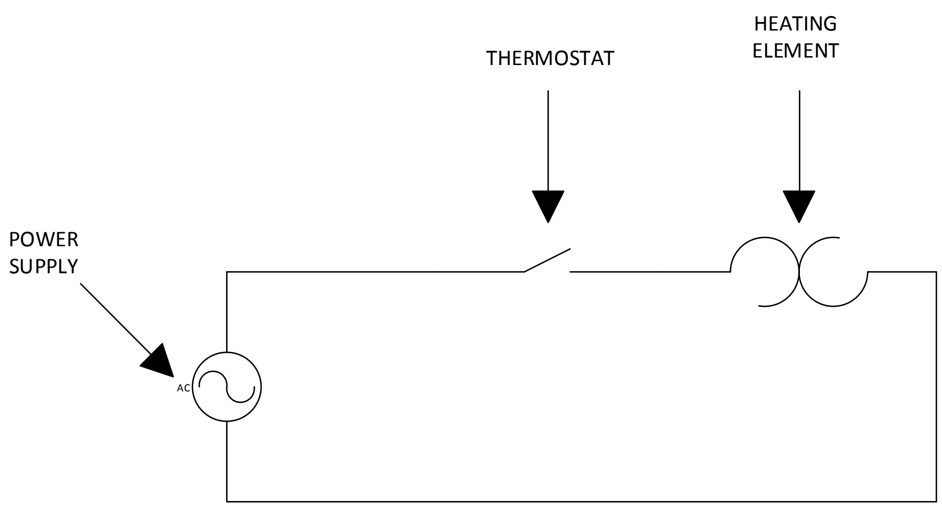


Figure 2. 8 Heating Circuit (Power)

The thermostat

Thermostats are found in most Irish homes and a common use for them is to control the temperature of the water in domestic immersion tanks. The thermostat is a device that measures the temperature of the water and opens and closes its contacts to regulate the temperature of the heating system in which the thermostat is a component of. The thermostat will usually have a controller called a thermostatic controller that is used to alter the temperature output from the heating system; this system is shown in figure 2.9.

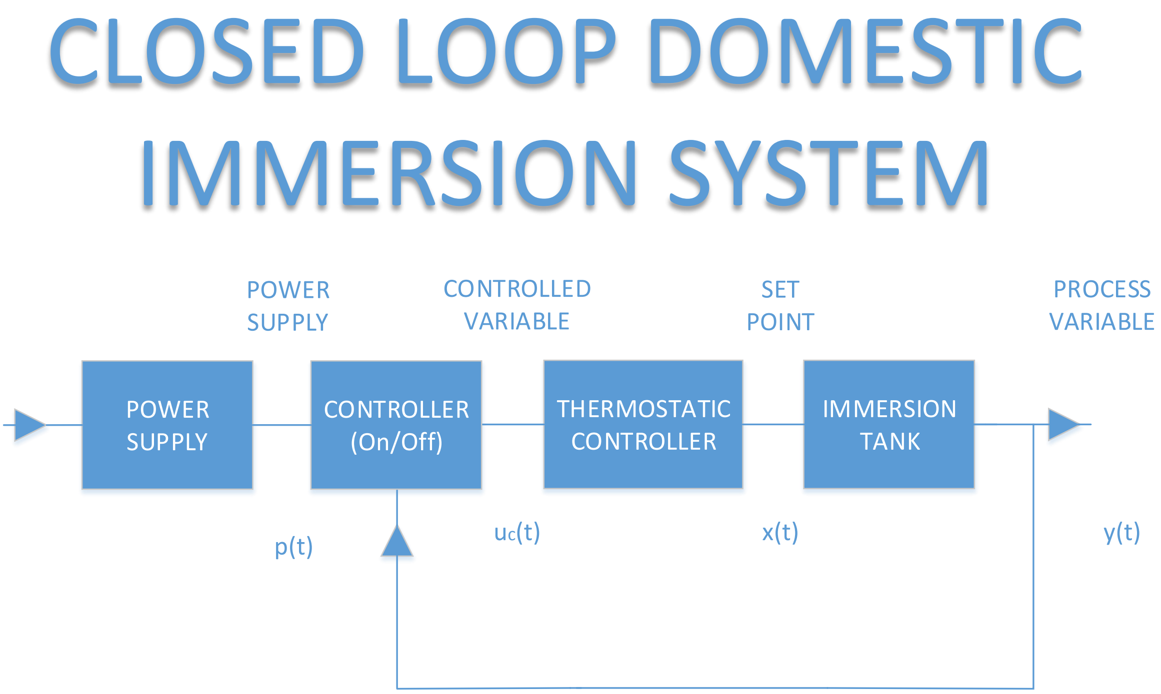


Figure 2. 9 Closed Loop Domestic Heating System

When the desired temperature for the tank is reached the thermostat will open its contacts thereby cutting off the electrical power supply to the immersion tanks heating element. Once the water in the tank cools to a certain level the contacts on the thermostat close and the power supply is again delivered to the heating element, this cycle is repeated continually until the power supply is removed from the system. From monitoring this cycle the level of hysteresis can be found, the level of hysteresis being the temperature range in which the thermostat opens and closes its contacts, the hysteresis range and a PRC for this system is shown in figure 2.10.

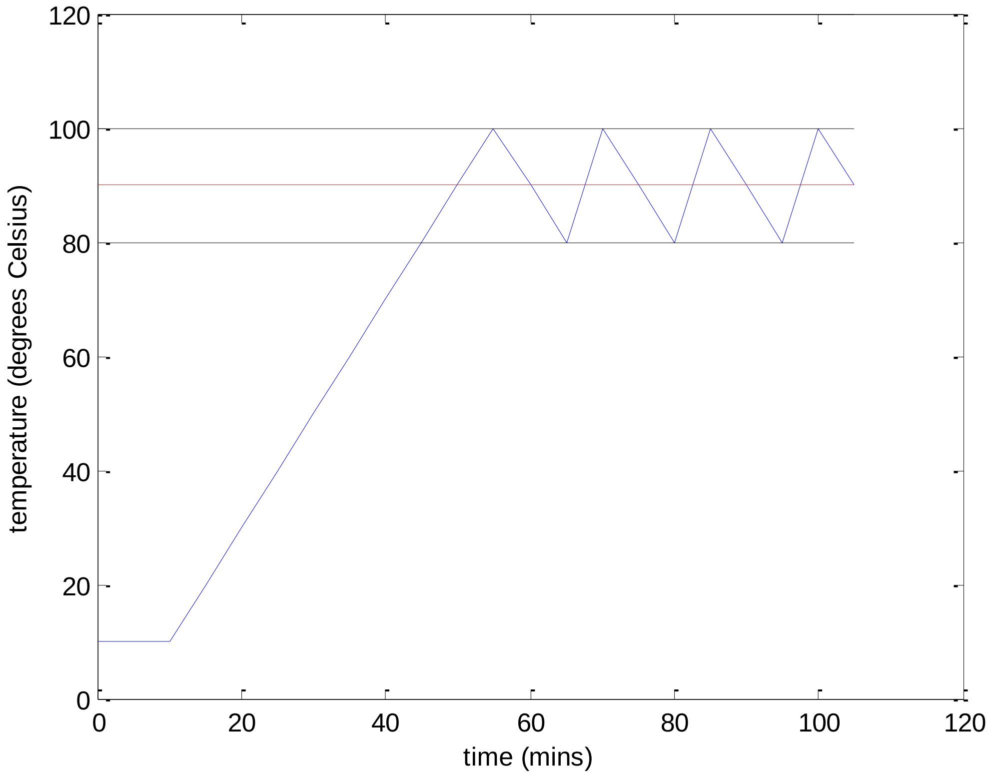


Figure 2. 10 Hysteresis Effect

There are several issues with using this from of control those being:

- The input to the system must be constantly turned on and off to maintain a value as close to the set point as possible.
- A low level of hysteresis gives a PV closer to the SP but at the expense of increased action from the actuators and therefore increased degradation of the systems moving parts which may not be designed for rapid and continuous action.
- A system which caters for rapid and continuous action from its actuators will consist of components of a higher quality than a system that doesn't, this increase in quality of components usually translates in an increased initial outlay for the components and also increased maintenance costs.
- Precise control of the system is impossible with this form of control, an example of this can be seen in figure 2.10 above where the SP is 90^{O}C and the PV is alternating between 80^{O}C and 100^{O}C which translates to an error of +/- 11.11%.

The above control system is found in many homes in Ireland and it is a good system for the initial outlay when a certain amount of error is tolerated. In the case of a system that requires precise control such as the Batch Reactor this closed loop system is not good enough and an improved form of control must be implemented, a form of controller that can deliver the necessary performance to control the temperature of Batch Reactor is the PID Controller.

2.8.2 The PID Controller

The most prevalent form of controller is the PID controller also known as the three term controller. The term PID is an acronym for Proportional Integral Derivative with each of the three terms describing the mathematical operation performed on the error signal, it has been shown in the previous section that a closed loop system produces an error signal by subtracting the PV from the SP, the outputs of each section of the controller are summed together to produce a controlled signal Uc, the output of the controller is then sent into the plant altering the dynamics of the plant in the goal of producing a process variable signal equal to the set point value. The actions performed by each section of the controller are now introduced:

P: In the Proportional Section of the controller the error is scaled by the Proportional gain K_p. The level of error correction provided by the proportional section of the controller is proportional to the size of the error, this means that the greater the error (the difference between the SP and the PV) the greater the output from the P section

I: In the Integral section of the controller the error is scaled by the Integral gain K_i and then integrated. The integral section of the controller is used to reduce constant errors by summing the error over a period of time, this is done by integrating the area between the x-axis and the curve/trend representing the Process Variable, due to the nature of integration large errors can occur even if the difference between the SP and the PV is relatively small through the accumulation of a small error over time.

D: In the Derivative section of the controller the error is scaled by the Derivative gain K_d and then differentiated. The Derivative section of the controller is concerned with the rate of change of the error and the output from this controller is directly related to the frequency at which the error is changing. A system utilising a PID controller is shown in figure 2.11.

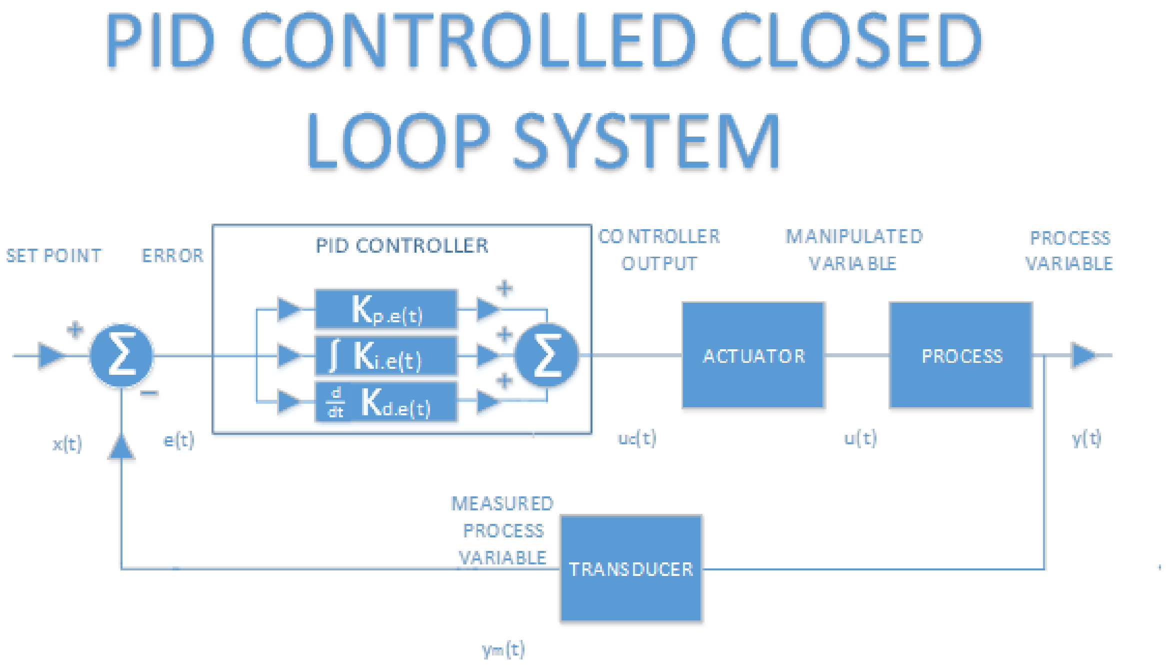


Figure 2. 11 PID Controlled Closed Loop System

When designing a PID controller it is prudent to keep the design as simple as possible and therefore if one of the P, I or D control elements is not necessary then it should not be included. In industry there are three common forms of PID controller found those being P, PI and PID, a brief overview of each controller is now given:

The P-Controller is the simplest and most robust controller. It is the easiest controller to tune with this controller having the quickest reaction to disturbances and deviations from the Set Point. It is because of the controller's reaction speed that this form of controller is utilised as the inner controller of a cascade controller architecture. The controller's rapid reaction to disturbances is utilised to maximum effect providing stability to the system by dealing with inner loop disturbances and therefore restricting the action of the systems primary controller. The negative aspect of using the P-Controller is the steady state error commonly associated with this controller and therefore it is not suitable to be used in isolation.

The PI-Controller is the industry controller of choice, the integral component of the controller counteracts the steady state error associated with the P-Controller introduced from the proportional component.

The derivative term of the **PID-Controller** allows the engineer to use stronger gains in the P and I components in comparison to a P or PI controller without reaching the critical gain values at which the PID controlled system may become unstable. The PID controller is utilised with systems that have a large amount of dead time and also those which respond slowly to disturbances. The PID Controller should not be used in noisy environments or with control systems which respond rapidly to disturbances as the degradation due to the rapid use of the systems actuators will most likely be unacceptable.

PI and PID Controller Characteristics

PI

- Compensator increases the system type by one, which helps with error control.
- Increases phase-lag at low frequencies.
- Generally, increases damping, rise times, settling times and reduces overshoot.
- Decreases bandwidth.
- Not sensitive to high frequency noise.
- Acts as a low-pass filter.

PID

- Combined effects of PI and PD compensation.
- Cascade of a PI and a PD compensator.

Performance Criteria

Ultimately the engineer must design the best 'fit for purpose' controller, this may be done by a trial and error approach by tuning the controller gains K_p, K_i and K_d. The term fit for purpose is largely concerned with the performance criteria that a controller is judged against those being rise time, steady state error and in the case of systems greater than first order overshoot with the PID controller components P, I and D addressing these issues respectively, the fourth performance variable of interest is the system settling time which is a consequence of overall controller design. The system dead time is an inherent characteristic of the system and therefore the PID controller has no influence over this parameter. The first 4 performance criteria listed below are analysed in the time domain with the last 2 listed being analysed in the frequency domain.

- The Rise Time is generally characterised as the time the output takes to go from 10% of the final output value to 90% of the final output value.
- The Steady State Error is the difference between the desired output value and the actual system steady state value.
- The Maximum Overshoot when evaluated against the system steady state value gives the largest error value greater than the steady state response.
- The Settling Time is the time it takes from a system input to the time the system settles to within a percentage range of the steady state output commonly 2% but this figure will depend on the process under control.
- The Dead Time is the time it takes from a system input to the time at which the system displays a clear output response.
- Phase Margin represents how much phase may be lost from the closed loop system before the system becomes unstable.
- Gain Margin represents how much gain may be added to the system before the closed loop system becomes unstable, a common way of expressing this value is in decibels (dB).

Controller gains: The table below indicates the effect the Proportional, Integral and Derivative gains have on system performance characteristics, rise time, settling time, overshoot and steady state error.

Controller Gains	**System Performance Characteristics**			
	Rise Time	**Over Shoot**	**Settling Time**	**Steady State Error**
K_P	**Yes**	**Yes**	**None**	**Yes**
K_I	**Yes**	**Yes**	**Yes**	**Can Eliminate**
K_D	**None**	**Yes**	**Yes**	**None**

Table 2.1

2.8.3 Controller Tuning: Ziegler Nichols

The Zeigler Nichols tuning rules are a way of obtaining initial gain values for any form of PID controller, the Ziegler Nichols tuning formulas are shown in table 2.2.

Ziegler Nichols Table of Tuning Formulas

Table 2.2

Controller Type	Proportional Gain KC	Integral Time τI	Derivative Time τD
Controller Type	Proportional Gain KC	Integral Time τI	Derivative Time τD
Proportional	$\frac{1}{K_p}\left(\frac{\theta_d}{\tau}\right)^{-1}$	....	....
Proportional plus Integral	$\frac{0.9}{K_p}\left(\frac{\theta_d}{\tau}\right)^{-1}$	$3.33\times\theta_d$	....
Proportional plus Integral plus Derivative	$\frac{1.2}{K_p}\left(\frac{\theta_d}{\tau}\right)^{-1}$	$2\times\theta_d$	$0.5\times\theta_d$

Where: K_P is the process gain

Θ_d is the dead time.

τ is the system time constant

τ_I is the integral time

τ_D is the derivative time

Once the values of τ_I and τ_D have been found the Integral gain K_I and the derivative gain K_D may be calculated.

Calculating the Integral Gain $K_I = \dfrac{K_C}{\tau_I}$

Calculating the Differential Gain $K_D = K_C \times \tau_D$

Algorithms used in Gain Form

Proportional (P) Controller: $u(t) = k_c e(t)$ (1st order equation)

Proportional plus Integral (PI) Controller: $u(t) = k_c e(t) + k_i \int e(t)dt$ (2nd order equation)

Proportional plus Integral plus Differential (PID) Controller: $u(t) = k_c e(t) + k_i \int e(t)dt + k_d \dfrac{de(t)}{dt}$ (3rd order equation)

The continuous time PID controller using the PID 3rd order equation is shown in figure 2.12 below.

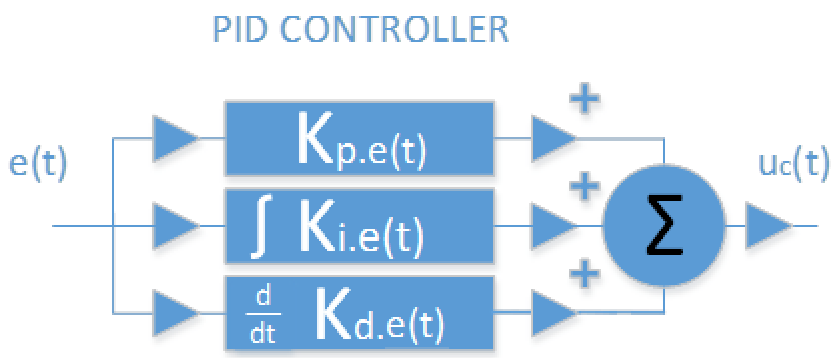


Figure 2. 12 PID Controller Time Domain

Control theory and therefore the PID controller is often expressed in the frequency domain using Laplace transforms, the PID controller algorithms expressed in this manner are now shown in industrial form and textbook form.

Algorithms used in Frequency Domain

$$E(s)K_c(1+\frac{1}{\tau_i s}+\tau_d s)$$

$$E(s)(K_c+Ki\frac{1}{s}+K_d s)$$

The PID controller in frequency domain notation is shown in figure 2.13 below

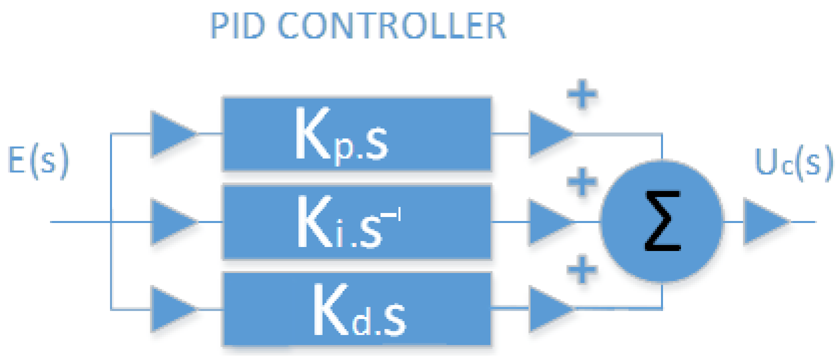


Figure 2. 13 PID Controller Frequency Domain

Any section of the controllers shown in figures 2.12 and 2.13 may be altered by adjusting the relevant time, by setting the derivative time to zero a PI controller will be implemented, or by setting the integral time to infinity a PD controller may be implemented.

The controller designed using these tuning rules will give an ok controller for a system however further tuning will more than likely be required to meet the desired performance criteria. It must be noted the tuning rules shown in table 2.2 are not the only Ziegler-Nichols tuning rules and in fact there are many other forms of tuning rules including Cohen-Coon, ITAE, Ciancone-Marlin as well as graphical tuning methods such to mention just a few methods.

2.9 Cascade Control

Cascade Control is used to improve the response of a system to disturbances and/or to a change in Set Point. For cascade control to be implemented there must be at least two processes taking place, this means that for n processes where n is any integer number greater than one then a maximum of n controllers can be implemented in the system with each controller requiring its own feedback loop, it must be noted however that each process may not necessarily require its own controller. Figure 2.14 shows a system consisting of two processes and two controllers.

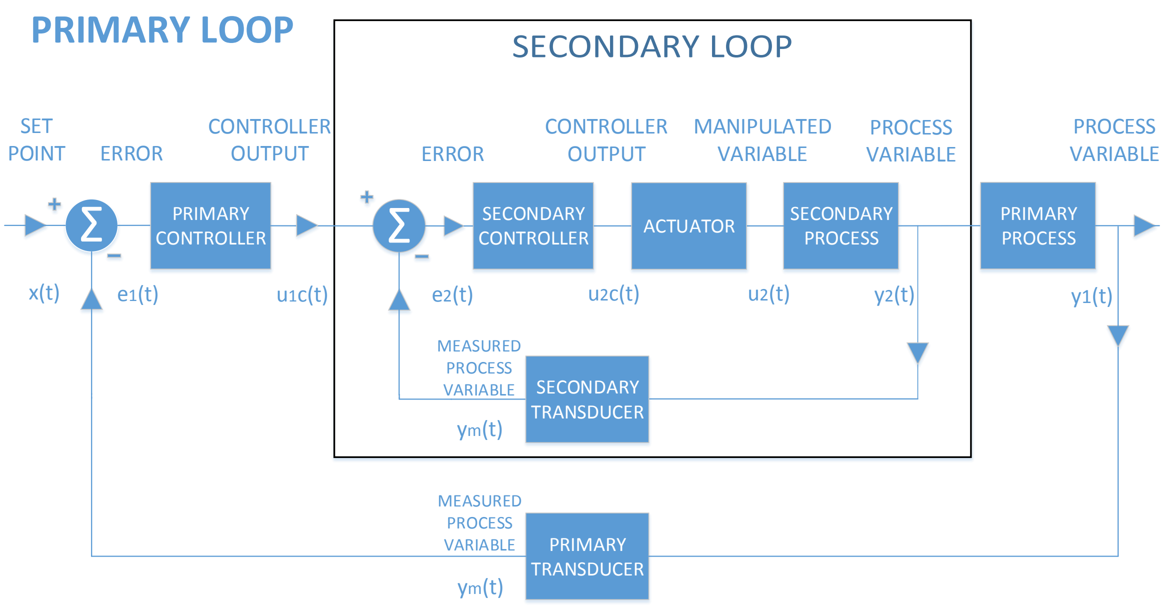


Figure 2. 14 Complete Closed Loop System

With the control system set up as shown in figure 2.14 the primary controller regulates the primary controlled variable, if split range control is employed this controller may control two variables e.g. temperature and flow rate. It can be seen from figure 2.14 that the output of the secondary controller is the input to the secondary process, with this architecture any disturbance that affects the secondary process will be attenuated before the primary process is affected. For the secondary controller to do this effectively however requires that the Relative Response Time RTT of the secondary loop to be three to five times faster than that of the primary loop [14].

In many systems there are usually points at which the system is vulnerable to disturbances, if a disturbance is introduced to the same system as shown in figure 2.15 below then the secondary loop controller is placed at the point where the disturbance is introduced to the system and when tuned correctly reduces the effect of the disturbance to the system.

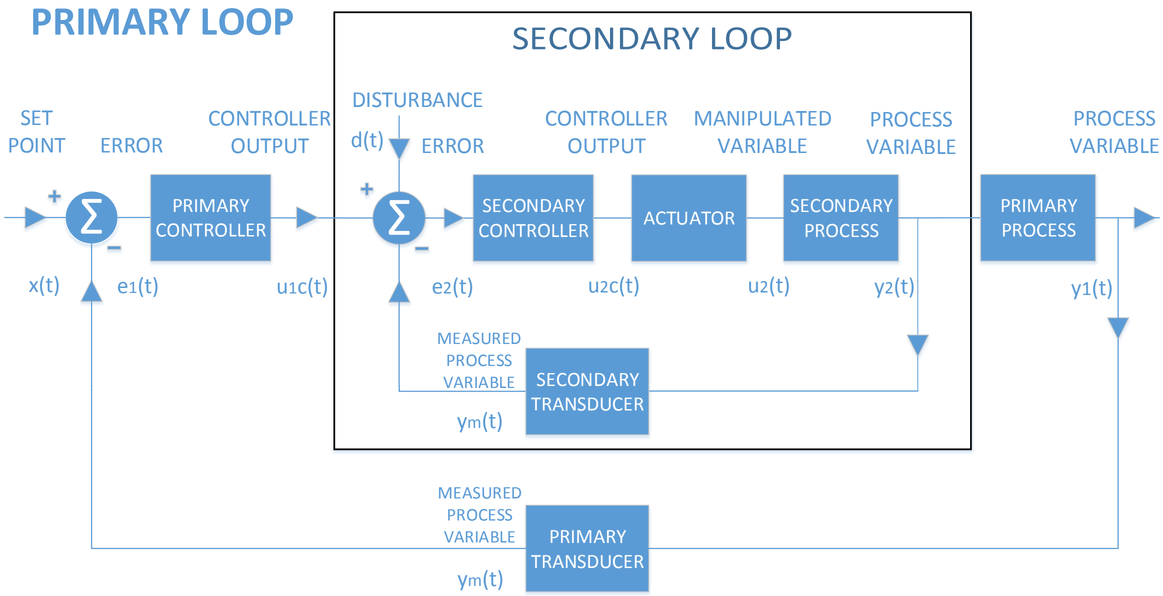


Figure 2. 15 Complete Closed Loop System with Disturbance

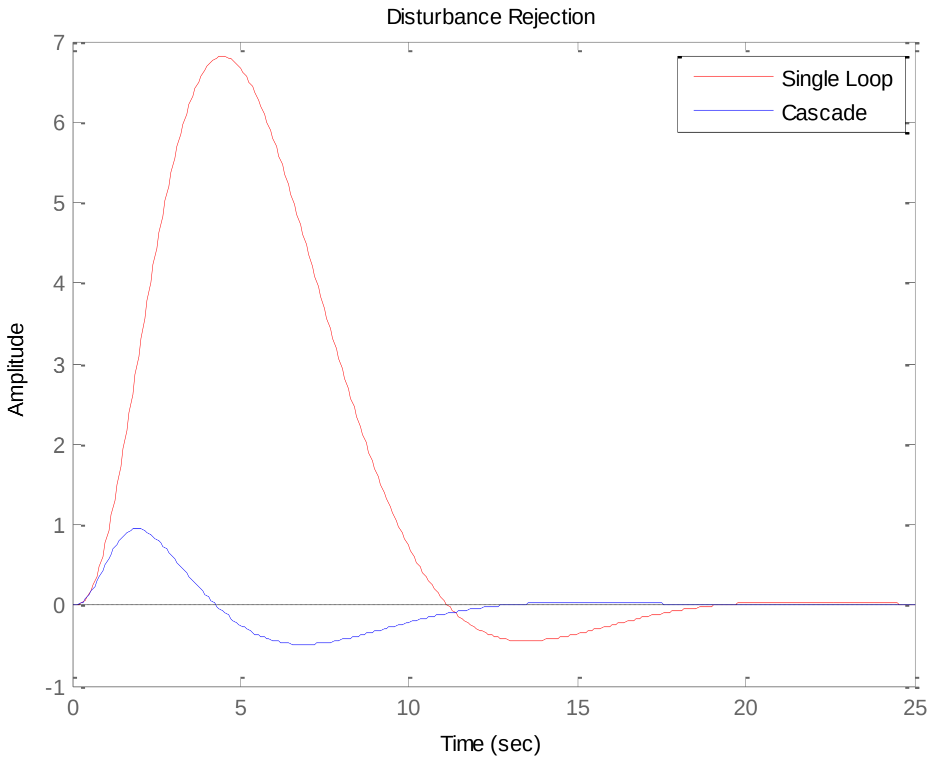


Figure 2. 16 Controller Architecture effect on Disturbance Response

Figure 2.16 clearly displays the benefits of using a cascaded controller architecture as has been shown in figures 2.14 and 2.15, the red plot in figure 2. 16 shows the effect a disturbance has on a system with a single controller and the blue plot shows the effect a disturbance to the system has on a cascaded controller architecture, it must be noted however that the system that the output responses are taken from in figure 2.16 has a secondary process with a much shorter time constant than the primary loop which leads to improved system stability.

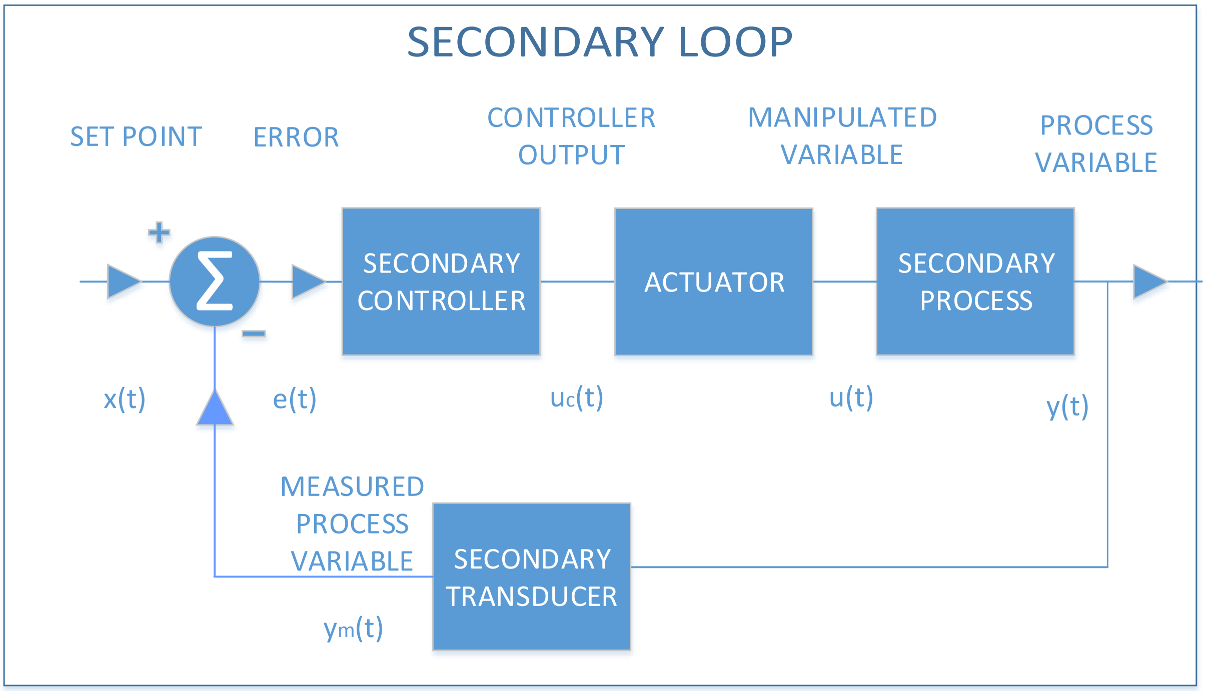


Figure 2. 17 System Secondary Loop

To successfully implement this form of control both controllers must be correctly tuned, to do this the secondary controller must be tuned first, only the secondary loop of the system shown in figure 2.14 is of concern and this is shown in isolation in figure 2.17. Once the secondary controller has been tuned the primary controller can be tuned, when tuning the primary controller the secondary controller should be placed in automatic mode.

2.10 Split Range Control

Split Range Control is a form of Selective Control with Selective Control commonly being employed on systems that have fewer Controlled Variables (CVs) than Manipulated Variables (MVs). With Split Range Control the CVs are divided into ranges with each range assigned to a MV, in this way a single CV such as temperature may be regulated by two MVs and the offset associated with systems with less CVs than MVs can potentially be eliminated [8]. In the case of a Batch Reactor the CV could be temperature or flow, if the CV is temperature the MVs could be heating and cooling, if the CV is flow the MVs could be inlet flow and outlet flow. Figure 2.18 shows the relationship between a single CV and two MVs, MV1 and MV2, where it can be seen that the choice of MV and the percentage operation of MV is a function of the Controller output.

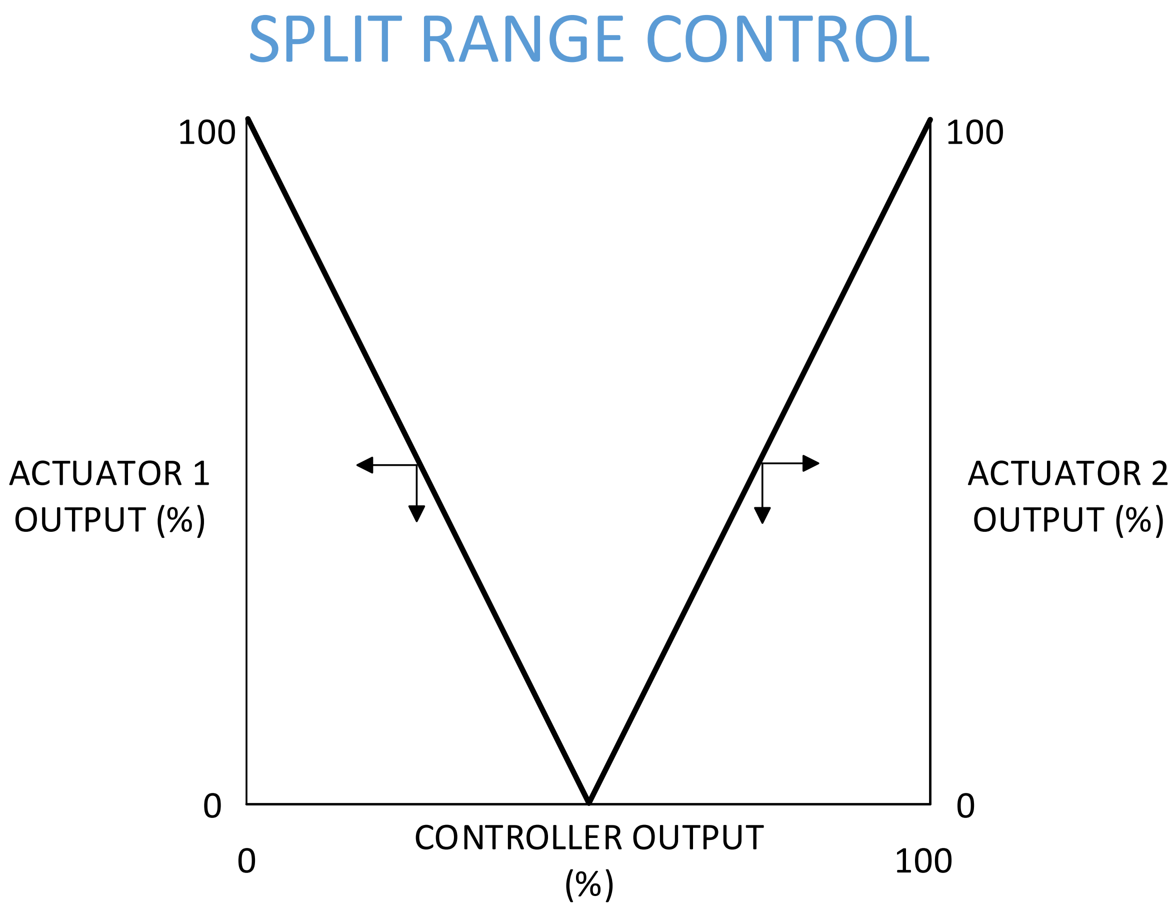
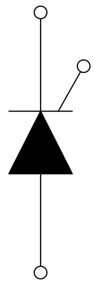


Figure 2. 18 Split Range Control

2.11 Phase Angle Control

The SCR

The Silicon Controlled Rectifier (SCR) is a robust semi-conductor device that can take voltage and current levels of 1000's of Volts and Amps respectively. The SCR is very similar in construction and operation to the diode in that the device must be forward biased for conduction to occur but unlike the diode the SCR has a gate that must be triggered by a current source for conduction to take place. It is the gate of the SCR that allows for phase angle/voltage control, the SCR is shown in physical form in figure 2. 19 and in semi-conductor form in figure 2.20.



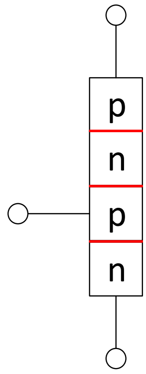


Figure 2. 19 SCR Physical   Figure 2. 20 SCR Semiconductor

A way of understanding the operation of an SCR is to model the SCR using two transistors (PNP and NPN), this is shown in semiconductor form in figure 2.21.

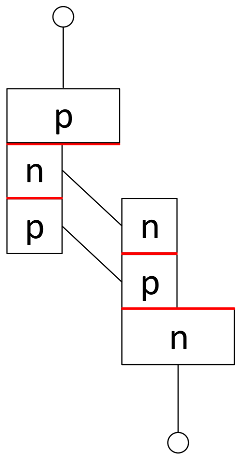


Figure 2. 21 PNP-NPN

It can be seen in figure 2.22 that the base of the PNP transistor is connected to the collector of the NPN transistor and that the collector of the PNP transistor is connected to the base of the NPN transistor this is shown in figure 2.22 below. For the purpose of describing the operation of the SCR the PNP transistor will be referred to as Q_1 and the NPN transistor will be referred to as Q_2 this is shown in figure 2.23 below.

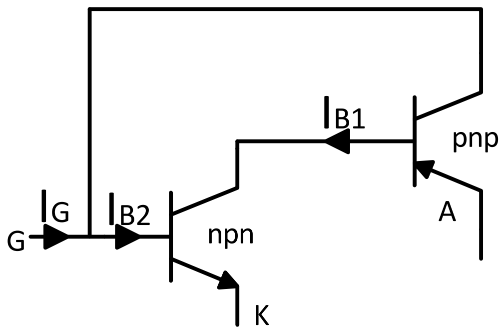


Figure 2. 22 SCR Circuit 2

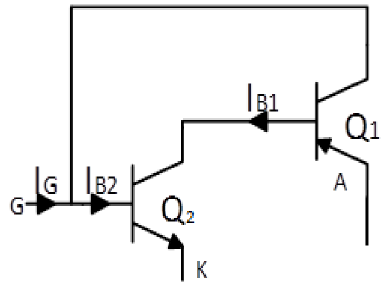


Figure 2. 23 SCR Circuit 1

The SCR as shown in the figures above has three terminals, an Anode, Cathode and Gate. The Anode is where current enters the SCR, the Anode being the emitter of the PNP transistor. The Cathode is where current leaves the SCR, the Cathode being the emitter of the NPN transistor. The Gate controls whether the SCR will enter conduction mode or not.

Operation of the SCR using the two transistor model

When the gate current I_G is zero as shown in figure 2.24 the SCR acts as a diode in the off state i.e. an open switch. When a positive pulse of current is applied to the gate both transistors will turn on provided the Anode of the SCR is positive wrt to the Cathode, this can be seen in figure 2.24. I_{B2} turns on Q_2 thus providing a current path for I_{B1} into the collector of Q_2 and therefore turning on Q_1. The collector current of Q_1 provides extra base current for Q_2 with Q_2 conducting after the trigger pulse has been removed. Q_2 sustains the on-state of Q_1 by providing a path for the current I_{B1} and Q_1 sustains the on-state of Q_2 by providing a path for the current I_{B2} thus the SCR stays in conduction mode via regenerative action.

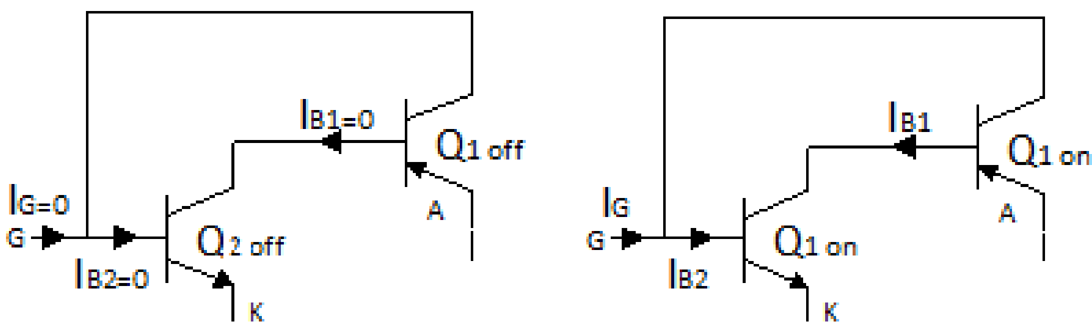


Figure 2. 24 SCR Circuit 3

Operating voltages and currents

Once the SCR is Forward Biased it still needs a pulse of current to turn it on, there is a minimum current called the holding current (I_H) which must be reached for the SCR to turn on and stay on, I_H can typically range from 5mA to 40mA depending on the power rating of the SCR.

The SCR will be turned on when I_H has been reached but will not conduct current. For the SCR to conduct current the Latching current (I_L) must be reached, I_L must be greater than I_H.

Turning the SCR off

There are two ways to turn the SCR off while the SCR is conduction mode.

(i) Reverse the supply voltage so that the Cathode of the SCR is made positive wrt the Anode.

(ii) Bring the Anode current to zero.

Calculating the Average value of the voltage

If the AC voltage has a frequency of 50Hz, then one cycle of the AC voltage waveform will take 1/50Hz=20ms, where each cycle constitutes one revolution and therefore 360^O.

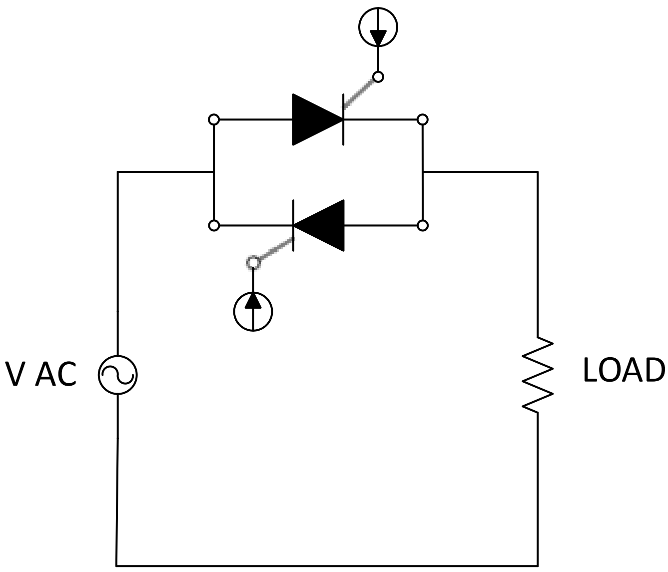


Figure 2. 25 Single Phase Voltage Control Circuit

If the pulse from the current source starts at 0ms then the firing angle = $360^O \times \frac{\phi}{20}$ the firing angle being used to represent the point in a sinusoidal wave at which the SCR is triggered into conduction mode with the negative to positive zero crossing of the sine wave taken as 0^o.

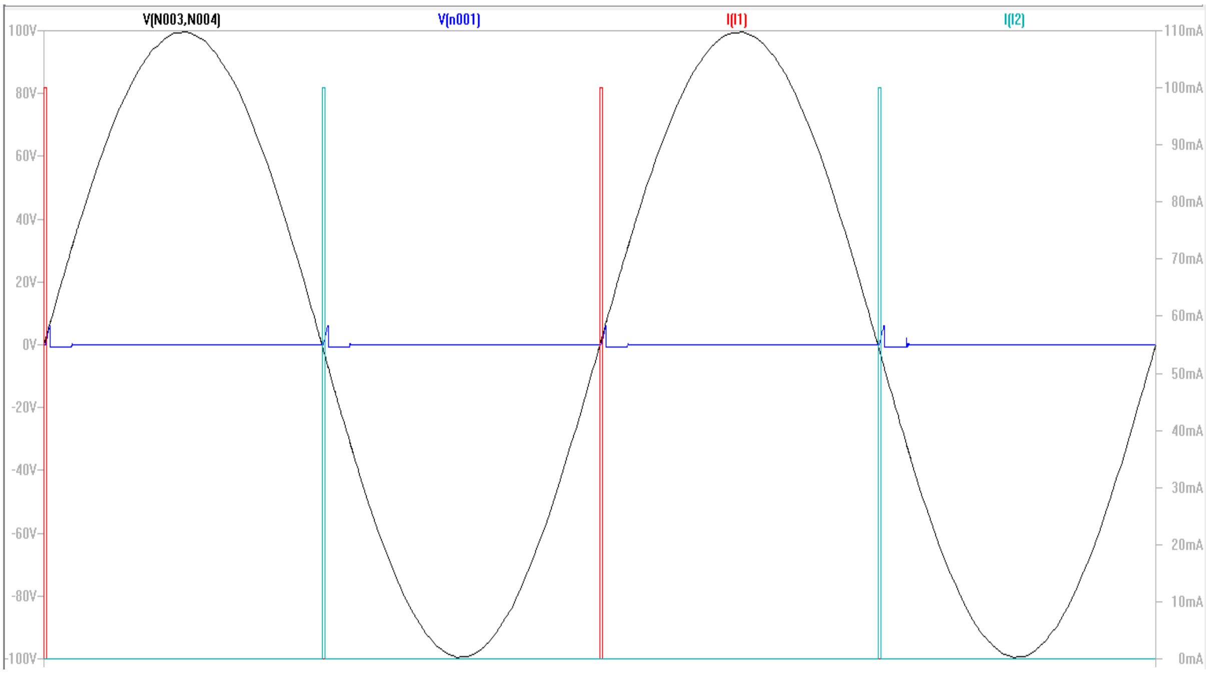


Figure 2. 26 Voltage Control Output Waveform

Figure 2.26 shows the output voltage V_{out} across the load when both SCRs as shown in figure 2.25 conduct for 180^{o} of the voltage cycle, the point at which each SCR enters conduction mode can be found by examining the red and blue current pulses associated with S_1 and S_2 respectively.

In general when the firing angle of $S_1=\alpha$ and the firing angle of $S_2= \alpha+\pi$ then the average voltage V_{avg} may be calculated by integrating the area between the sine wave and the zero crossing, so taking the first half cycle of the sine wave shown in figure 2.26 gives $V_{avg} = \int_{\alpha}^{\pi} V_p \sin(\omega t) d\omega t$

Integrating the above equation then gives $V_{avg} = V_p \left| -\cos(\omega t) \right|_{\alpha}^{\pi}$

2.12 Pulse Width Modulation

Understanding PWM is an extremely useful tool for any engineer, PWM can be used to control the amount of DC voltage to many devices and actuators, including that of the motor where it is used for controlling the rpm of the motor.

Shown in figure 2.27 is a 10 V DC signal in the top plot and a 0 V DC signal in the bottom plot.

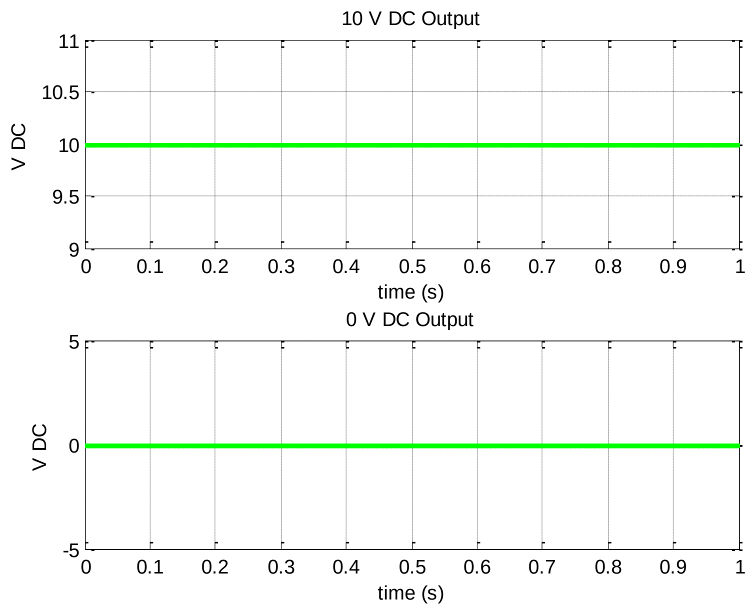


Figure 2. 27 DC Signals

Now if a 10 V DC power supply is switched on and off at a fixed frequency e.g. at 50% duty cycle the output will be 10 V DC half of the time and 0 V DC the other half of the time, this results in an average voltage of 5 volts. This is shown in figure 2.28.

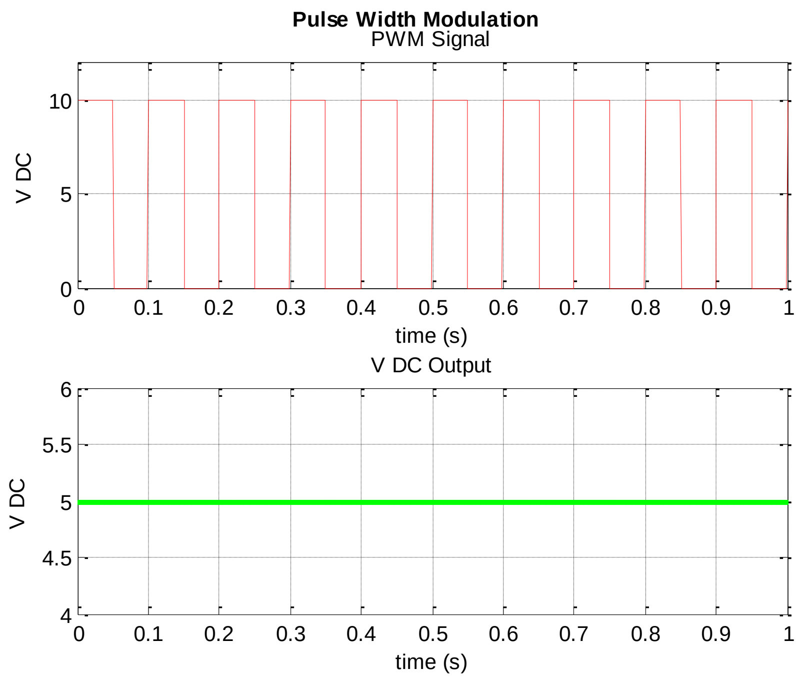


Figure 2. 28 PWM Output

From the above description and by viewing figures 2.27 and 2.28 it can be seen that changing the pulse width i.e. duty cycle changes the average voltage delivered to a device, this practice is known as Pulse Width Modulation which is usually abbreviated to PWM.

The circuit diagram of speed control circuit utilising PWM is shown in figure 2.29.

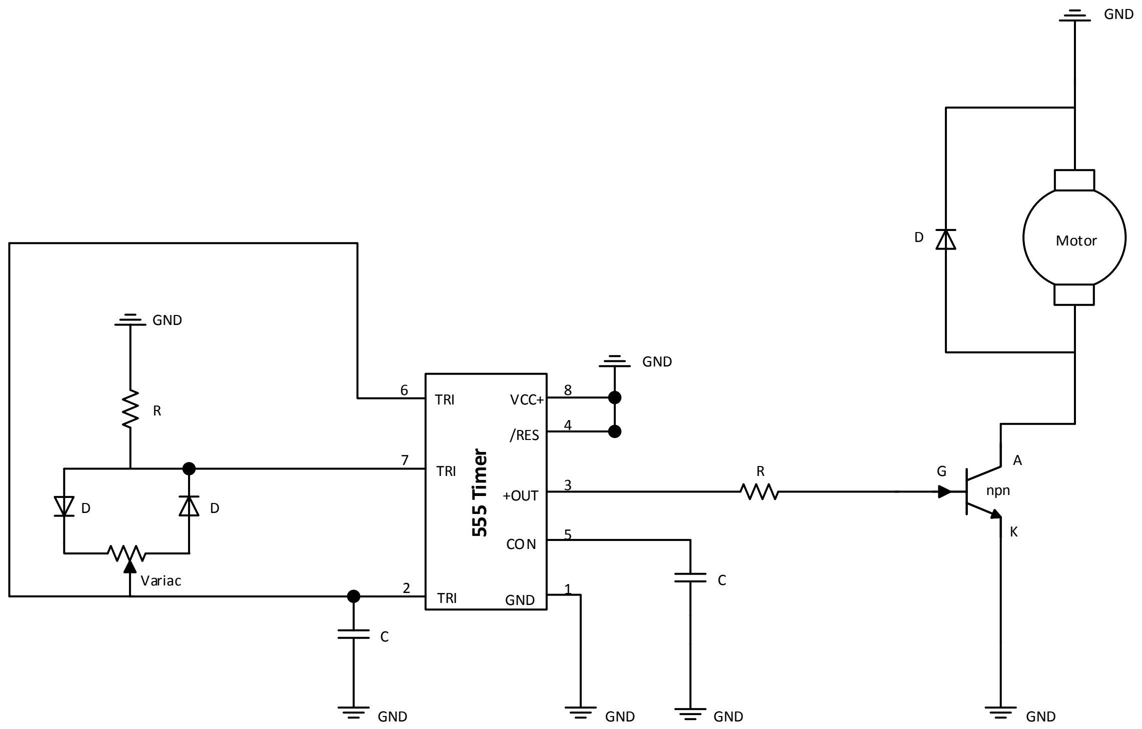


Figure 2. 29 PWM Speed Control Circuit

The key component of figure 2.29 is the 555 timer. The 555 timer when configured as shown in figure 2.29 outputs a square wave that is pulse width modulated. In the circuit shown above the duty cycle is changed by altering the variac. The circuit also consists of an NPN transitor which is used to switch in loads that are too large for the 555 timer to supply.

2.13 Scada

SCADA stands for Supervisory Control And Data Acquisition, from this acronym it can be taken that:

- **Supervisory:** Process real time information will be presented to the engineer.
- **Control:** The process will be controlled by the system.
- **Data Acquisition:** Real time data will be recorded.

A SCADA system provides a facility for tuning of process control loops and acts as the engineer's interface to the system meaning that direct access to the PLC(s) may not be required. Usually the SCADA system will be password protected; this is to prevent unauthorised operation/alteration to the system. A typical SCADA screen is shown in figure 2.30.

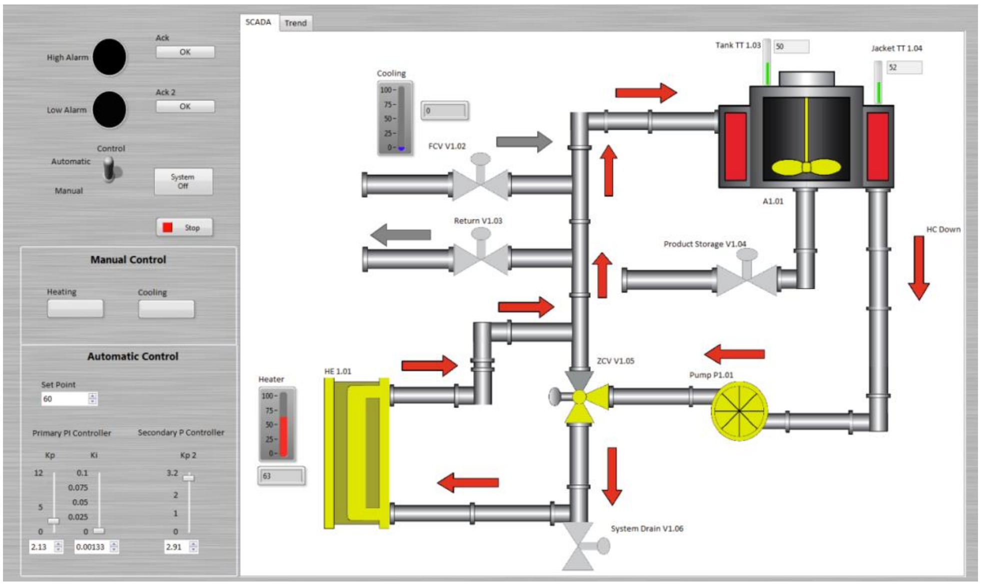


Figure 2. 30 Example SCADA Screen

There are many factors and opinions that will govern how the screens for a SCADA system will be designed, two of the most important being the colours used and the positioning of the commands on the main screen.

Colours used

Choosing the right colours on a SCADA system may seem like a simple task however mistakes have been made in the past and will continue to be made in the future; figure 2.31 shows an acceptable use of different colours and an unacceptable use of different colours.

Acceptable	**Unacceptable**
Green	Red
Red	Green
White	Yellow
Yellow	Blue

Figure 2. 31 Acceptable/Unacceptable Colour Combinations

It can be seen that it is easy to differentiate the colours and the associated names of the colour on the LHS of figure 2.31, conversely it is difficult to see the colours and associated colour names on the RHS, from this it is easy to imagine how a SCADA screen with a white background and yellow text and trends would make a poor user-interface [15].

Screen Locations

For a screen with no stimulus there are certain quadrants of the screen that will receive more attention than others, this is shown in figure 2.32

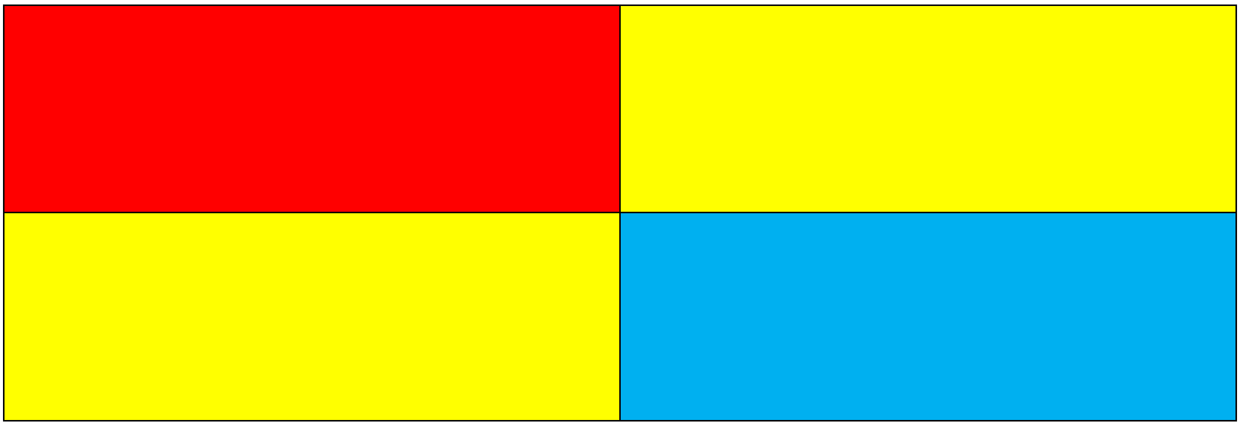


Figure 2. 32 Quadrants by Interest

The red quadrant is the section of the screen that will receive the most attention, followed by the two yellow quadrants and finally the quadrant receiving the least attention being the blue quadrant. It has been shown that users of interactive systems such as SCADA systems do not read everything on a screen but instead scan the screen [16], the area of the screen that people tend to focus on takes an F shape. This corresponds with the thoughts that have been expressed regarding figure 2.33 and the research undertaken by the Nielsen Norman Group who specialise in Evidence-Based User Experience Research, Training, and Consulting.

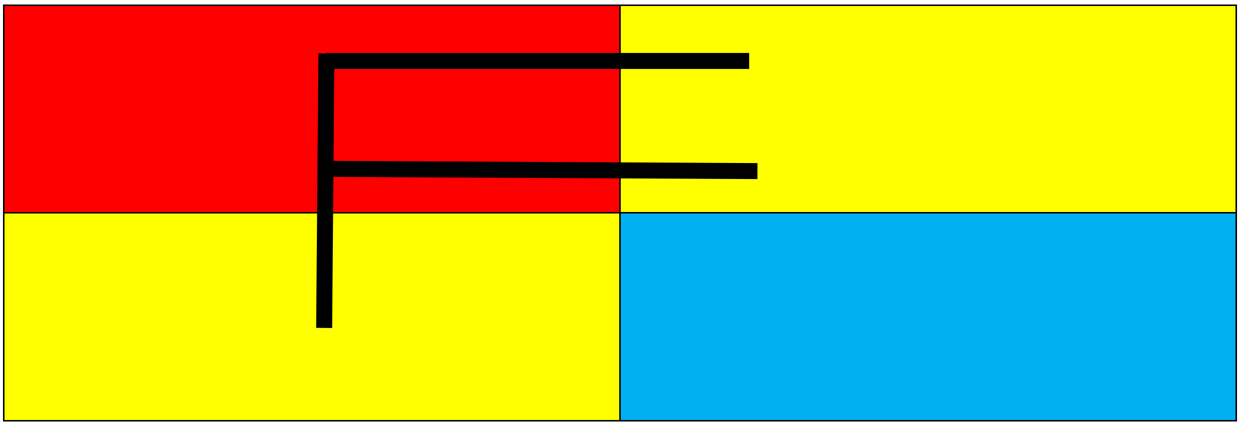


Figure 2. 33 The F Pattern

The development of a SCADA screen can take a huge amount of effort and the planning and design of these screens is to a large extent associated to the field of Ergonomics. When designing the screens some of the questions that should be asked are:

- Should you use text or images?
- Replicate toggle and push button switches?
- Who is going to be using the interface?
- What industry are the users in?
- What culture are the users from?

The above questions are in no way a comprehensive list of questions that must be asked when designing SCADA screens but questions that should definitely be answered and form a solid basis from which to design fit for purpose SCADA screens.

3. Methodology

3.1 Introduction

The process to be controlled in this project is a pilot scale batch reactor. The reaction vessel is constructed from stainless steel which is the usual material used in the fabrication of Reaction Vessels (in industry glass lined steel reactors are commonly found) found in the pharmaceutical industry. Stainless steel is used because of its anti-corrosive and good heat conduction properties. The capacity of the reaction vessel is 3.5 litres and that of the heating/cooling system (jacket and piping) is five litres. The ¾ inch copper piping is the same type found in most domestic heating systems. Integral system components include the Pt100 temperature sensors, the 2.75 kW heating element and the systems actuators, these are listed in the systems I/O table shown in table 3.1 below.

Reference No.	Description	Manual/Auto	On/Off or Modulating	Comments
A1.01	Agitator	Auto	On/Off	24 V DC On
HE1.01	System Heating Element	Auto	Modulating	0-230V AC
C1.01	Heating Contactor	Auto	On/Off	24 V DC On
C1.02	Pump Contactor	Auto	On/Off	24 V DC On
P1.01	Circulating Pump	Auto	On/Off	Centrifugal Pump 230 V AC
TT1.03	Reactor Jacket Temperature Sensor	Auto	Modulating	Pt-100 Sensor 0-5 V DC
TT1.04	Reactor Temperature Sensor	Auto	Modulating	Pt-100 Sensor 0-5 V DC

V1.01	Pressure Safety Valve	Auto	On/Off	
V1.02	Flow Valve	Auto	Modulating	Type of Valve
V1.03	Return Valve	Auto	On/Off	2/2-way solenoid valve 24 V DC
V1.04	Product Exit Valve	Manual	Modulating	
V1.05	Circulation Control Valve	Auto	On/Off	3/2-way solenoid valve 24 V DC
V1.06	System Drain Valve	Manual	Modulating	

Table 3.1

A Piping and Instrumentation Drawing of the system which has been produced to ISA S5.1 standards is shown in figure 3.1, note how the tags shown in table 3.1 of the I/O list correspond with those shown in the P&ID, that is they interrelate with each other which is a good characteristic of core project documentation. Note the 230 V AC contactors shown in figure 3.1 have only been shown to inform the reader that the signals from the PLC are not powering HE1.01 and P1.01.

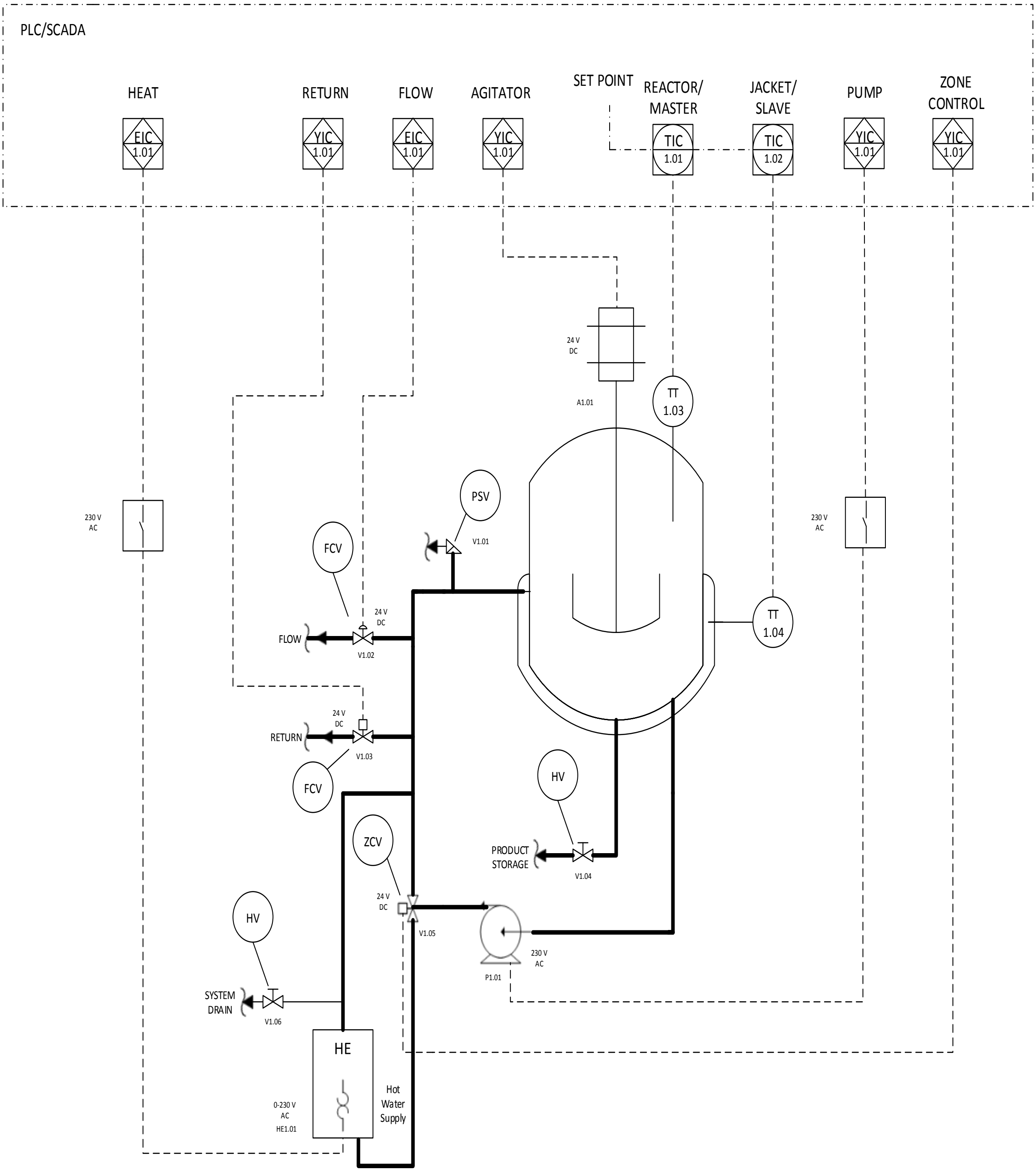


Figure 3. 1 P&ID

Figure 3.2 shows the pilot scale plant with all sensors and actuators labelled.

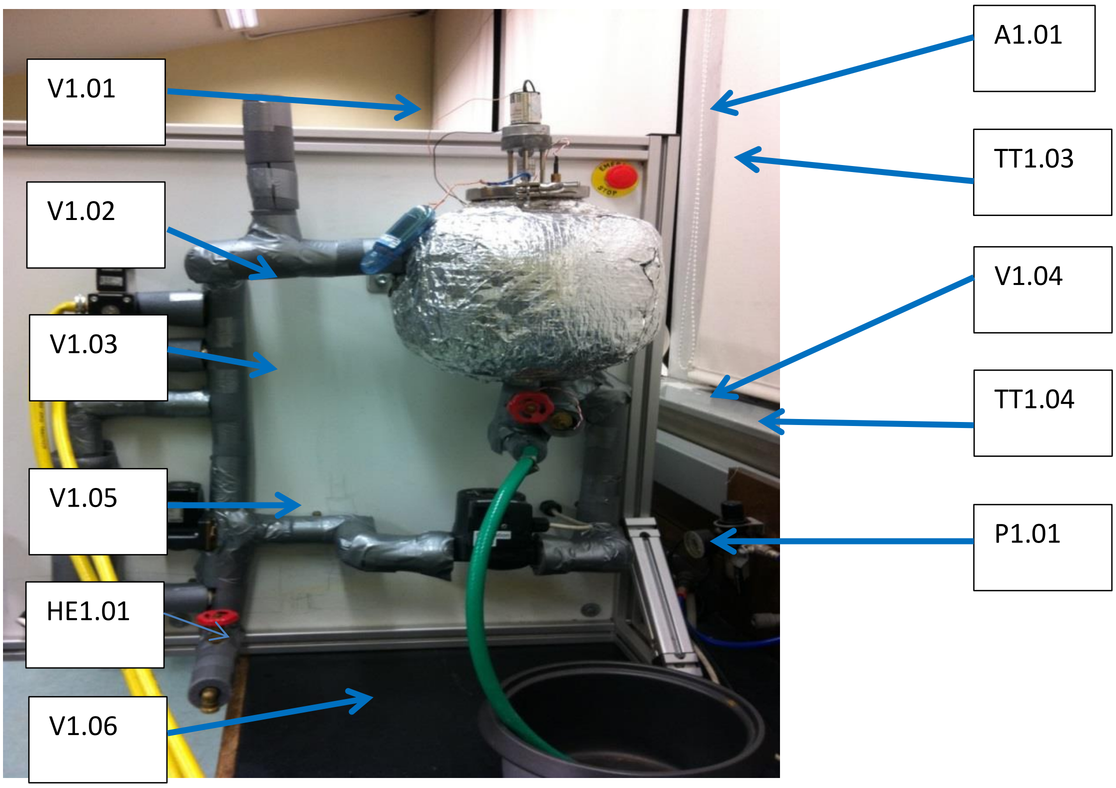


Figure 3. 2 Physical System

Figures 3.3 and 3.4 display the flow of fluid in the pilot scale batch reactor during both heating figure 3.3 and cooling figure 3.4.

Figure 3. 3 Cooling

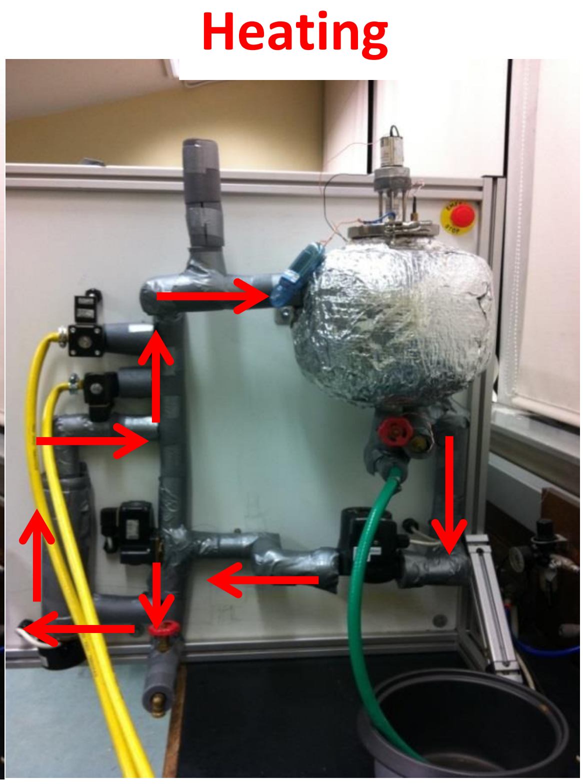


Figure 3. 3 Heating

3.2 Instrumentation and Calibration

Instrumentation and Calibration

The plant instrumentation consists of two Pt100 Resistance Temperature Dependant (RTD) sensors , Pt100 breaks down as Pt for platinum a pure metal, and 100 is the resistance of the sensor in Ohms at 0^{O} Celsius. The Pt100 resistance increases almost linearly with temperature and is usually expressed as either a linear or non-linear equation those being:

$$R(T) = R_0(1 + \alpha T)$$ Linear Equation

$$R(T) = R_0(1 + \alpha T + \beta T^2)$$ Non-Linear Equation

Where: R_0=100Ω

α=0.391 and β=5.85 x 10^{-7}

The Pt100 labelled TT1.03 in both the I/O list and the P&ID is installed in the reaction vessel (tank) and the Pt100 labelled TT1.04 is installed in the jacket, the leads from both devices are brought to individual transmitter bases where the resistance signal is converted to a 4-20 mA current signal, an ANSI standard range.

To calibrate the temperature sensors the leads from TT1.03 were disconnected and a decade box with a resolution of 0.1 Ω was connected to the transmitter base. The desired temperature range to be calibrated was 0-100^{O}C which corresponded to a resistance range of 100-138.51 Ω. The results of this calibration are shown in figure 3.5.

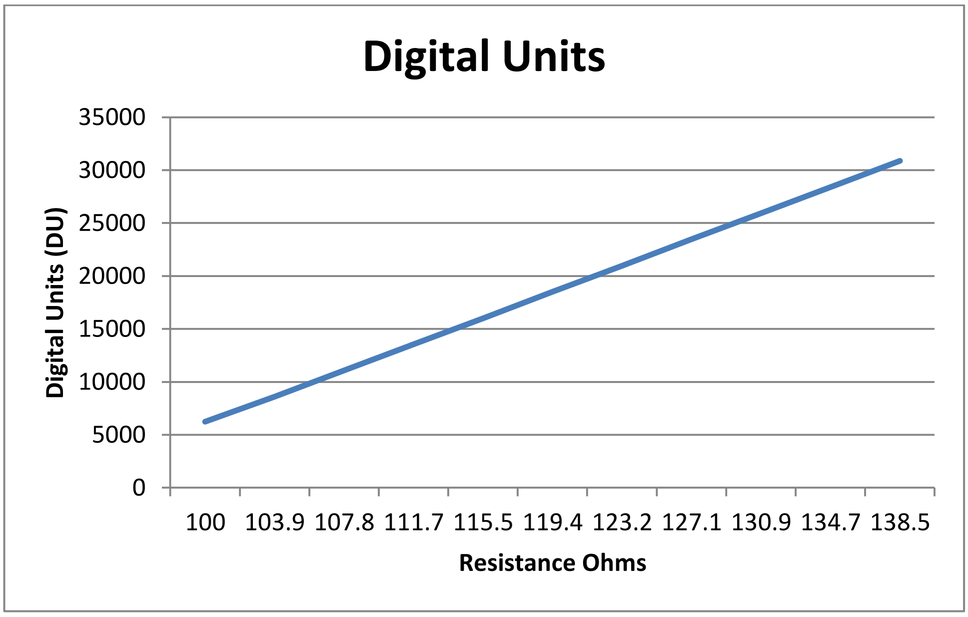


Figure 3. 4 DUs Vs Ohms

The MicroLogix PLC and associated A/D expansion module are 16 bit, the signal shown in figure 3.5 is signed meaning that there is a DU range of 2^{15}, it can be seen in figure 3.5 that most of this range is being used therefore providing a good resolution of the temperatures of both the reaction vessel and the jacket. To convert figure 3.5 to show the relationship between temperature and DU the resistance values shown on the x-axis were replaced with the corresponding temperature values in the Pt100 tables, this is shown in figure 3.6 where it can be seen that there is a relationship that is approximately linear between temperature and Digital Units.

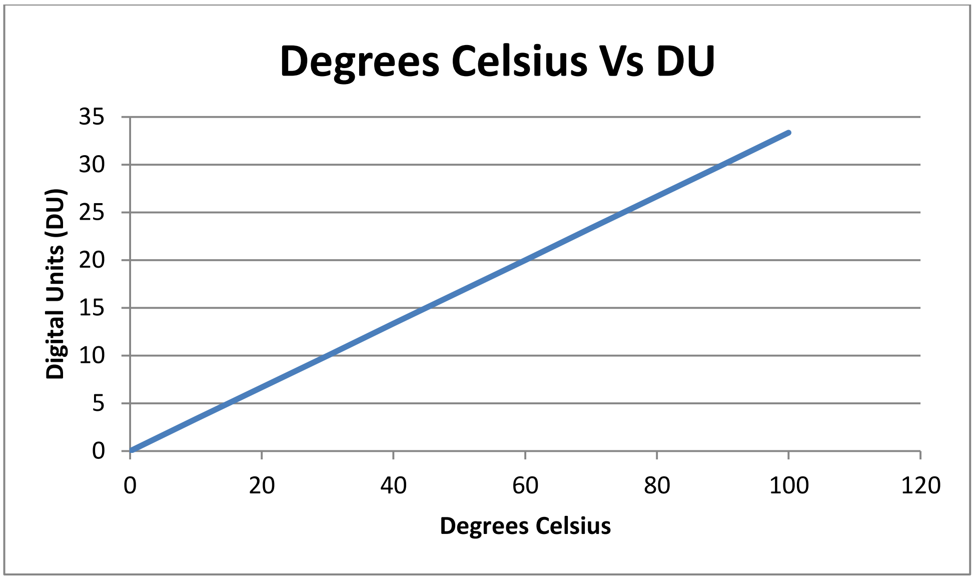


Figure 3. 5 DUs VS Degrees Celsius

Three calibration tests were undertaken and the results recorded are shown in table 3.2.

Resistance Ω	**Test 1 DU**	**Test 2 DU**	**Test 3 DU**	**Average DU**	Degrees **C**
100	6240	6248	6240	6242.66667	0
103.9	8584	8584	8584	8584	10
107.8	11080	11072	11072	11074.6667	20
111.7	13576	13560	13560	13565.3333	30
115.5	15992	16000	16000	15997.3333	40
119.4	18512	18504	18512	18509.3333	50
123.2	20952	20960	20952	20954.6667	60
127.1	23472	23480	23464	23472	70
130.9	25920	25936	25928	25928	80
134.7	28392	28400	28384	28392	90
138.5	30856	30864	30872	30864	100

Table 3.2

By analysing table 3.2 the slope of figure 3.6 can be calculated with the slope providing the relationship between the Digital Units and degrees Celsius.

Taking the values from Table 3.2 at at $0^{O}C$ and $100^{O}C$.

$$\frac{Y_2 - Y_1}{X_2 - X_1} = \frac{30864DU - 6242.67DU}{100^{O}C - 0^{O}C} = \frac{24621.4DU}{100^{O}C} = 246.214DU/^{O}C$$

3.3 Control and Communication

Introduction

This section of the methodology contains many brief sections on the control and the methods of communication of the process, each section has been condensed down as much as possible and is used to give a concise overview of the process, this section also complements the control philosophy in section 4.

Control System

The control system implemented in this report is comprised of an Allen Bradley MicroLogix 1100 system controller complete with an Allen-Bradley MicroLogix 1762-IF2OF2 analog input/output (I/O) module with SCADA screens for operator interface developed using the system design software LabVIEW. The MicroLogix 1100 system controller and the SCADA system are interfaced via the OPC package KEPServerEX.

Programming

The programme for the control and automation of the Batch Reactor is written to the PLC using the Rockwell automation software package RSLogix Micro English, this is a hybrid software programme utilising ladder logic and function blocks. This hybrid style of programming is shown in figure 3.7 where it can be seen that the ladder rungs implement logic running from left to right as per usual but function blocks may be implemented as outputs on the far right of the ladder rung. The PID algorithms written in this programme have a sampling period of six seconds.

Figure 3. 6 PLC Code Example

OPC

The acronym OPC stands for **O**bject Linking and Embedding for **P**rocess **C**ontrol. The OPC package KEPServerEX is used to interface hardware used in the process control of the PLC and the graphical based software application LabVIEW that is running the SCADA screens. The purpose of the OPC package is to translate the machine code produced by the PLC to a form that can be read and understood by a personal computer with a windows operating system.

During the programme all relevant signals and internal values are stored in memory locations in the PLC; the OPC server polls the PLC through a communications network and extracts information from any PLC memory location which has been ‘tagged’. The Tags must be pre-defined by the system designer and should be labelled according to its function for example TT1.03 should be the tag used for the reaction vessel temperature reading. Once the OPC tags have been read from the PLC they are passed on to the SCADA system at a sampling interval specified by the designer.

Communication

The SCADA facility is physically facilitated via an Ethernet cable connecting the PLC and the computer with the SCADA software. The communication between the PLC and the SCADA interface can take place over a network using either an Ethernet cable or a RS-232c cable, this would be the case for a full scale batch reactor where the process control of the system could be administered and monitored even from a different country to that of the batch reactor. To successfully create or alter the ladder logic programme created with Micro English to the PLC (an Ethernet device) the communications server RSLinx is used, RSLinx is also used to assign the PLC an IP address.

Signals

Analog Signals: The system analog module the Allen-Bradley MicroLogix 1762-IF2OF2 has the facility for two analog input signals and two analog output signals, if more analog input or output signals than this are required another analog module must be interfaced with the PLC.

Analog Input signals: The two system analog input signals originate from the Pt100 resistance thermometers that are installed in the reaction vessel and the jacket. As has been mentioned previously the leads of both Pt100s are terminated in Pt100 transmitter bases where the temperature dependant resistors produce a 4-20 mA current signal input to the PLC. Two 250 Ohm resistors have been installed across the two analog input terminals of the analog module, this will convert the 4-20 mA current signal to a 1 Volt to 5 Volt voltage signal. This was necessary due to the instrumentation set up that necessitates that the analog output signals have to be voltage signals. This conversion using Ohm's Law is shown below.

$$4mA \times 250\Omega \rightarrow 20mA \times 250\Omega = 1V \rightarrow 5V$$

Analog Output Signals: The 0-5 V DC analog output signals goes to a Phase Angle Controller which controls the magnitude of voltage present at the terminals of the heating element and therefore controls the level of heating to system. The 0-10 V DC analog signal goes to a modulating valve that is used to control the supply of cooling water to the system; the modulation of this valve is implemented via Pulse Width Modulation.

Boolean signals: The main PLC module works with Boolean signals, these signals are represented as 24 volts when high/true and 0 volts when low/false. The PLC Boolean inputs come from the E-Stop, the 230 V AC contactors for the heating element, the pump and the three 24 V DC relays, all the PLC Boolean inputs with the exception of the E-Stop are used for indication purposes only. The Boolean outputs are used to energise the three 230 V AC contactors and the three 24 V DC relays.

3.4 SCADA

Real-time control and data trending of the Batch Process is facilitated through KEPServerEX. A data-basing software package such as Microsoft Access can also be used for data logging. The user interface along with the installed sensors and actuators when programmed correctly allow for the manual and automatic control of the pilot scale batch reactor as well as safety protection via alarms and the facility for system shutdown. Alarm annunciation is provided for by alarm indicators on the SCADA interface. An alarm history may also be logged to the historian.

Only one pushbutton an emergency stop has been installed on the pilot scale batch reactor, all other functions are enabled via the user interface.

Interfacing the LabVIEW user interface with the PLC through LabVIEW allows for Supervisory Control And Data Acquisition of the process. The SCADA screens will present vital information to the operator regardless of whether the Batch Reactor is operating or not. The primary screen presents the operator with a fully functional user interface allowing for automatic and manual control of the process, real-time process information and also a graphical model of the system, this graphical model is based on the system P&ID. The second screen enables real time trending of the Process and Control Variables. On the primary screen the locations of the actuators and sensors of the pilot scale system are shown with all actuators and sensor tags corresponding with those documented in the P&ID and I/O list.

The flow of the controlled variable will be shown on the primary screen through the use of arrows. The sensor readings and the state of energisation of the actuators will be communicated to the user via the colour of the actuator. When the actuator is in use the colour of the actuator is yellow, when the actuator is not in use the colour of the actuator is that of the piping system this is shown in figures 3.8 and 3.9 respectively.

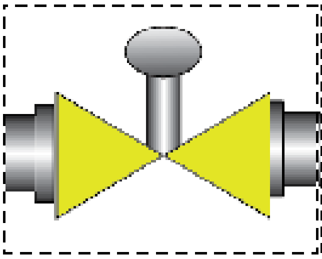


Figure 3. 7 Energised Actuator

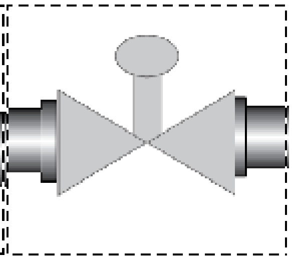


Figure 3. 8 De-energised Actuator

If the actuator is modulating then the percentage input to the actuator is displayed, this is shown in figure 3.10 where the heater output is at 63%.

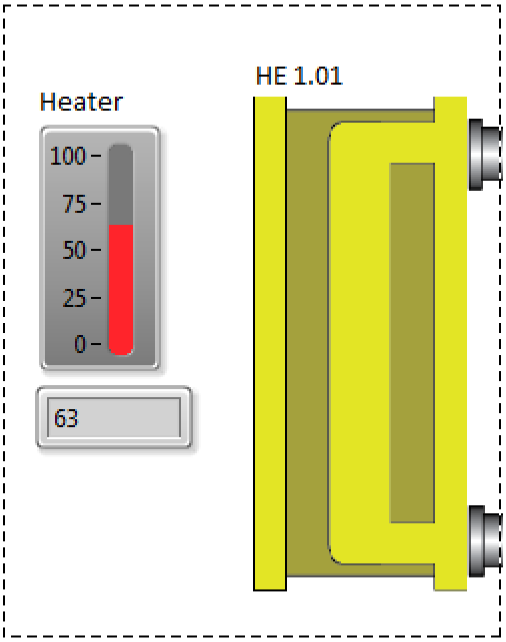


Figure 3. 9 Real Time Information

The temperature of the jacket & piping system the controlled variable (CV) and the temperature of the reaction vessel the process variable (PV) are displayed as a digital read out on the primary screen, this is shown in figure 3.11. Colour is used to indicate whether the process is either in a heating phase or a cooling phase, when the process is in a cooling phase the jacket & piping system, the flow of the liquid and the Reaction Vessel is blue.

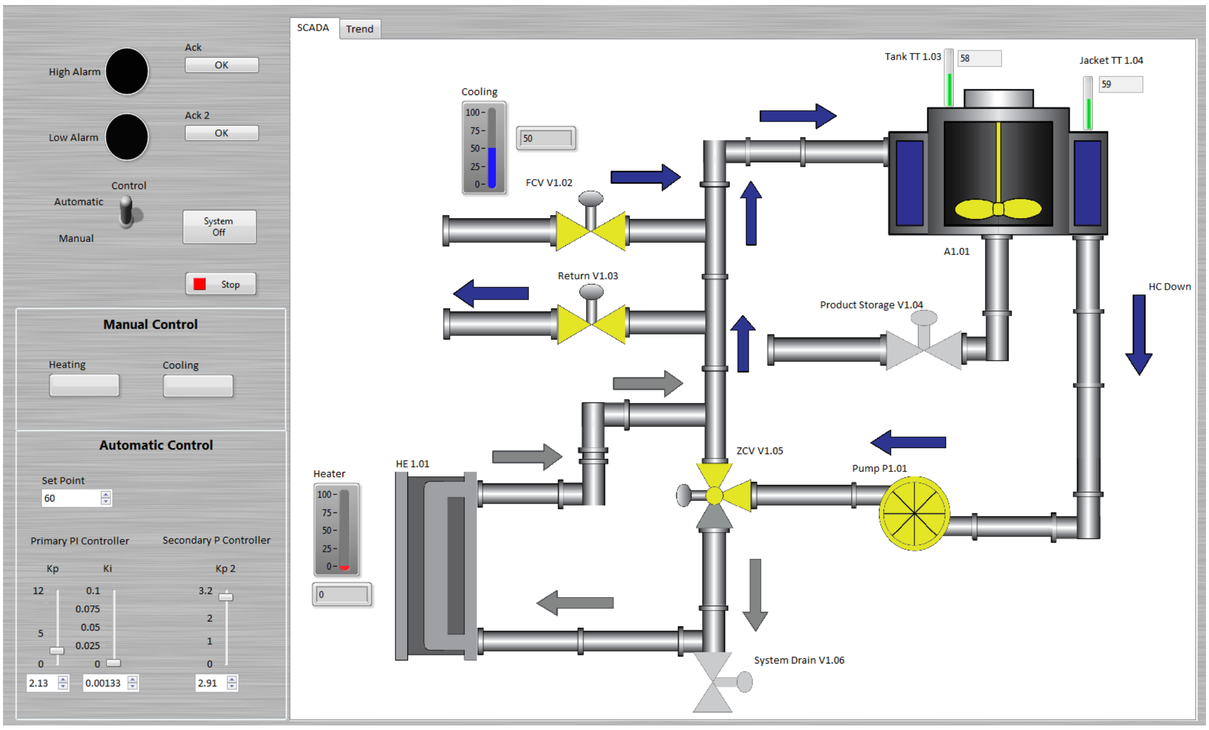


Figure 3. 10 SCADA Process Cooling Automatic

When the process is in the heating phase the jacket & piping system, the flow of the liquid and the Reaction Vessel are red, this is shown in figure 3.12. Note that figure 3.12 shows the process in a heating phase in manual control, it can be seen that the Automatic Control section of the screen has been faded indicating the system is under manual control.

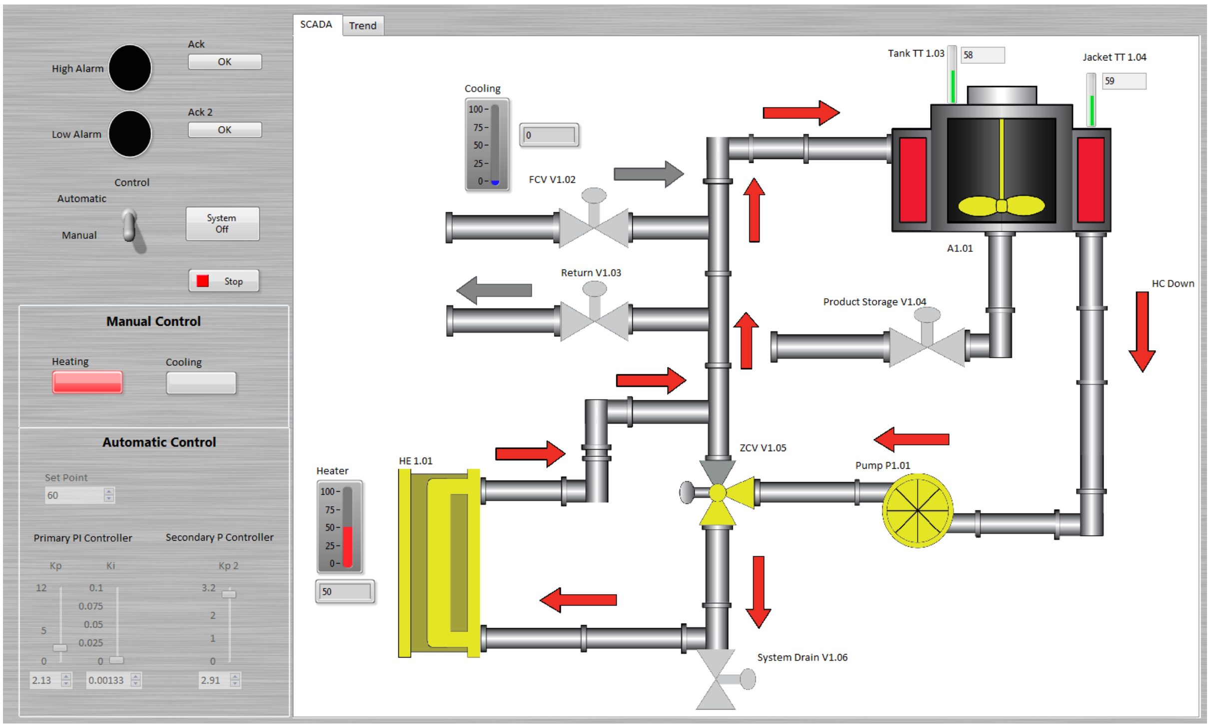


Figure 3. 11 SCADA Process Heating Manual

3.5 System Identification

System identification is used to approximate the system characteristics and in this project a Step Input was introduced to the system via the system heating element HE1.01 to obtain the system output response.

During the step test the step size was set at 20% of the heater output with 20% output corresponding to 550W, this test was unsuccessful as the temperature saturated at 80^{o}C the thermal limit of the thermostat, this failed test is shown in figure 3.13.

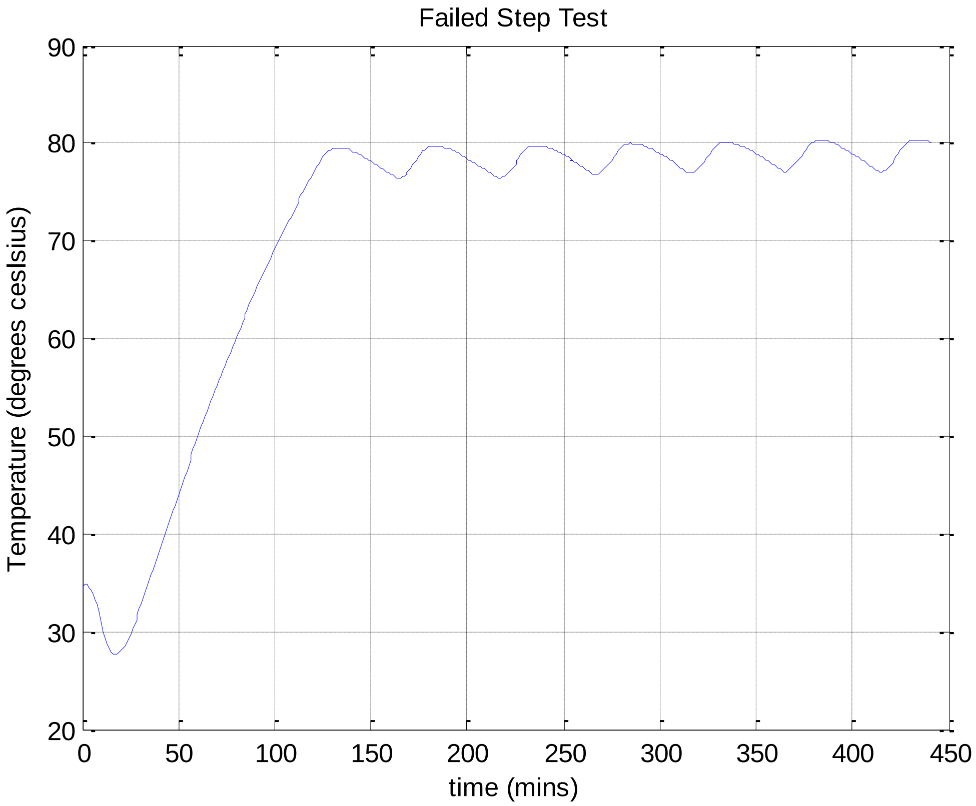


Figure 3. 12 Failed Step Test

After some research it was found that many Step Inputs fall between 2 and 5% of the total output range so the Step Input was reduced to 2.58% which gave an input to the heater of 71W. Figure 3.14 shows approximately 7 hours of recorded data for the jacket and the tank, the data being recorded between 11:52 a.m. and 6:54 p.m.

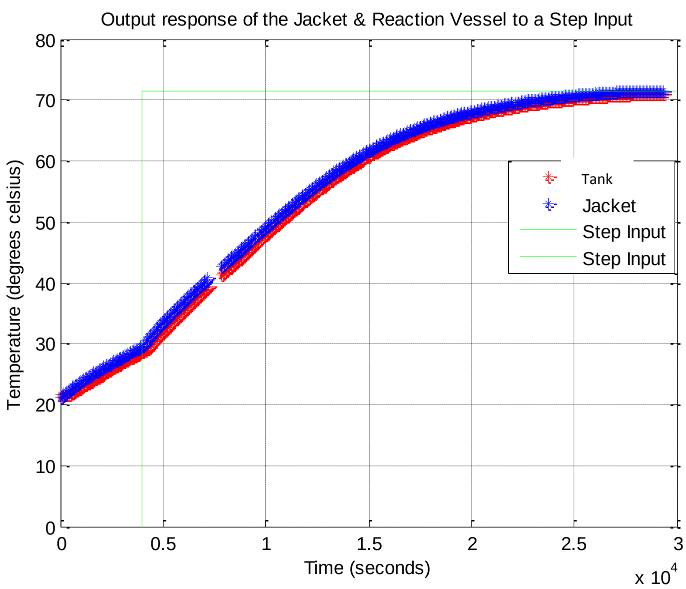


Figure 3. 13 Successful Step Test

It can be seen in figure 3.14 that the temperature of both the jacket and tank were ramping when the Step Input was introduced to the system, this was due to the pump, the pump was on for two hours before the Step Input was introduced to the system, one hour of which was recorded, since the pump is an integral part of the system this is an unavoidable disturbance.

The two point method was used on the process output, that is the output from the tank to derive a first order plus dead-time model for the complete process which encompasses both the jacket and the tank.

$$\tau = \frac{3}{2}(t_2 - t_1) = \frac{3}{2}(8391.5 - 3339.5) = 7578\,\text{secs} \;= 126.3\,\text{mins}$$

The overall process is presumed adiabatic and also that there is no loss of energy in the transfer of heat between the jacket and the tank, this means that the magnitude of the Step Input is presumed to be equal to the change in temperature resulting in a steady state temperature of 71.5 ^{O}C and therefore a gain of one, this can be seen in figure 3.14. This gain applies to the jacket, the tank and therefore the overall process.

The dead time of the jacket was graphically analysed and found to be 0 minutes.

This gave a transfer function of $\dfrac{K}{\tau s + 1} = \dfrac{1}{126.3s + 1}$

The two point method was also used on the output of the jacket to derive a first order transfer function as a part of the process of modelling the system as a second order plus dead-time model. Two methods were used were used to derive a transfer function of the tank those being taking the output of the jacket as the input to the tank and Smith's Method.

Taking the output of the jacket as the input to the tank

This involved breaking the input into a series of ramps and then analysing the corresponding section of the tank output to derive the transfer function of the tank. A section of the input to the tank is shown in figure 3.15.

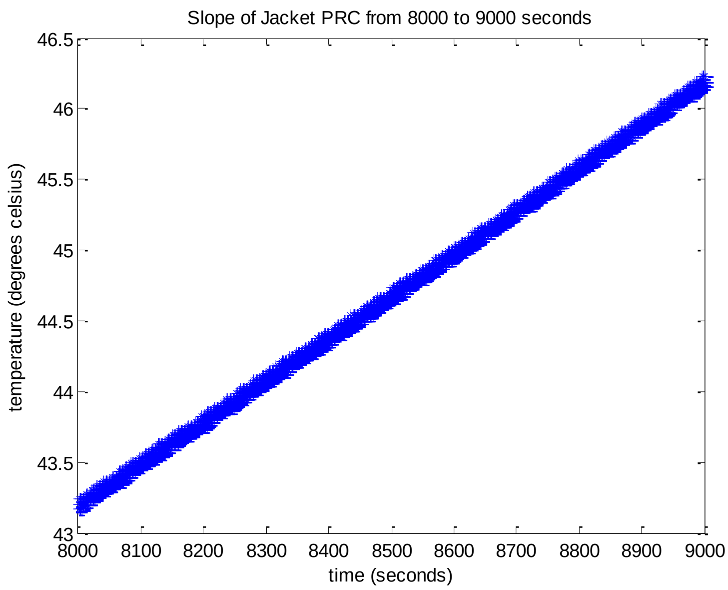


Figure 3. 14 Ramp Input

The mathematical representation of the output of the tank using this method is shown below

$$y(t) = ck\left(t + -\tau\left(1 - e^{\frac{-t}{\tau}}\right)\right)$$

Where: C is the ramping rate

K is the gain

τ is the time constant of the tank

y(t) is the Reaction Vessel output at time t.

This method proved unsuccessful as the time constant calculated for the tank yielded different values depending on the section of the jacket output response analysed.

Smith's Second Order Method

This method involved finding the 20% and 60% points from the output response of the tank and then subtracting any dead time from these points. The 20% point minus dead time was divided by the 60% point minus dead time. Using this value and the Smith's method chart shown in figure 2.7 a second order transfer function of the form shown below was derived.

$$G(s) = \frac{Ke^{-\theta_d s}}{\tau^2 s^2 + 2\varsigma\tau s + 1}$$

From mathematical manipulation and using the known value of the time constant the reaction vessel time constant was found to be 8.128 minutes. The dead time of the entire process was graphically deduced by analysis of the reaction vessel output response and found to be 4 minutes however as is the case with Smith's method the dead time was refined to produce the best system model giving a refined dead time of 2 minutes.

$$G(s) = \frac{Ke^{-\theta_d s}}{\tau s + 1} \; \frac{e^{-2s}}{8.128s + 1}$$

FOPDT

The FOPDT is an extremely useful model of a system that may be derived as long as the system output response resembles a Process Reaction Curve to some degree. The main value of FOPDT models is that they capture essential dynamic process features. Past results have shown that the FOPDT is adequate for use in advanced control strategies such as Smith Predictor and Feed Forward control [11]. It has also been documented that the majority of PID rules have been developed for FOPDT models rather than SOPDT and higher order models [10] so this model is worth deriving.

To derive a FOPDT model of the process the two point method was implemented on the Reaction Vessel Output response i.e. the process, this gave a time constant of:

$$\tau = \frac{3}{2}(t_2 - t_1) = \frac{3}{2}(8808 - 3725) \; \tau = 7624.5\,\text{seconds} = 127.1\,\text{minutes}$$

The dead time was found to be 4 minutes during the analysis of the reaction vessel time constant.

Again since the system is presumed adiabatic then through thermodynamic principles the Step Input must be the same value as the steady state output giving a gain of K=1.

This analysis resulted in the derivation of the following transfer function for the process:

$$G(s) = \frac{Ke^{-\theta_d s}}{\tau s + 1} = \frac{e^{-4s}}{127.1s + 1}$$

3.6 System Modelling

Once the characteristics of the sub-systems and the overall process as a FOPDT model had been derived the models could be implemented in Simulink a model based design package that is part of the Matlab suite.

An open loop system was developed and a Step Input was introduced replicating the open loop conditions that the actual step tests were performed under. Figure 3.16 shows the open loop models of the system.

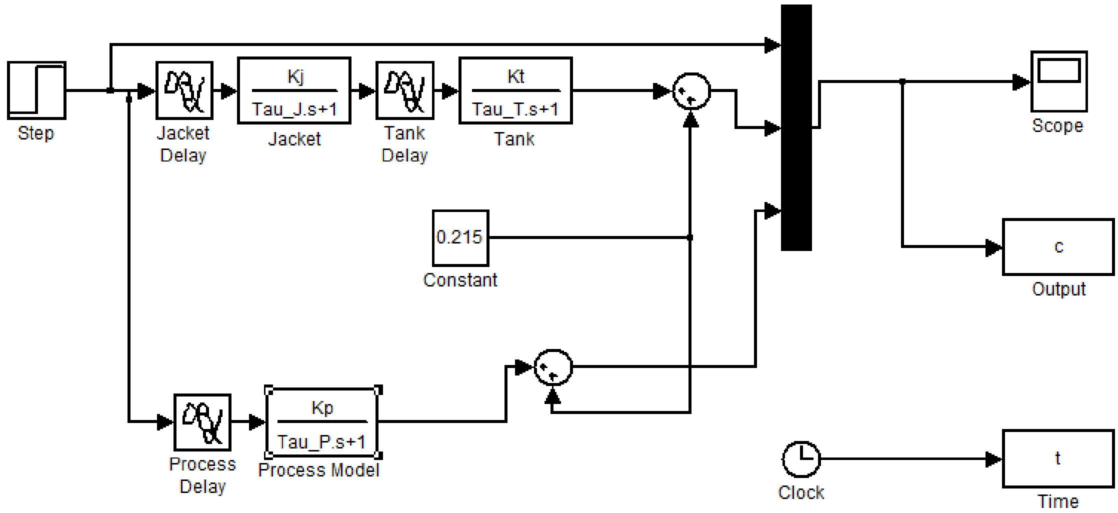


Figure 3. 15 1st & 2nd Order Simulink Models

The step response from the system shown in figure 3.16 was plotted against the recorded experimental process data and the models were then refined until the best fit models were developed, these models are shown in figure 3.17.

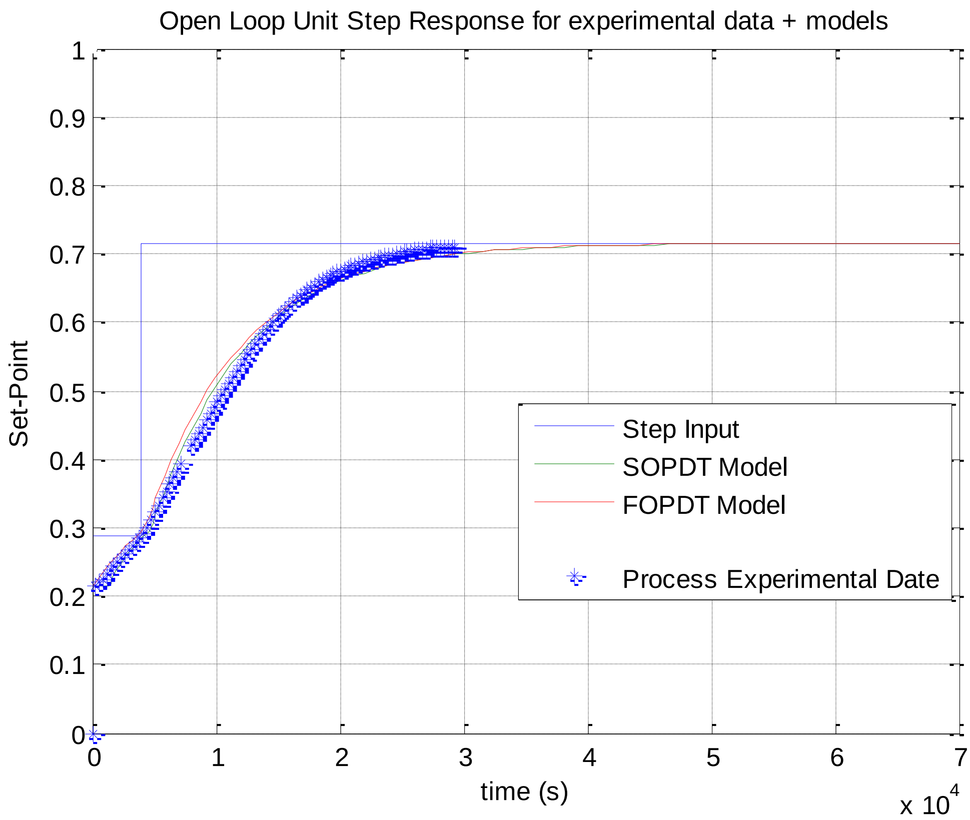


Figure 3. 16 Experimental Data

Through refining the models it was found that all the derived system characteristics were accurate apart from the process gains which were found to be: Kj=0.6996 for the jacket and Kt=1 for the tank. Because the overall process gain Kp is the product of Kj and Kt the process gain was found to be 0.6996, this was done by introducing a Step Input into the jacket in the system shown in figure 3. 18.

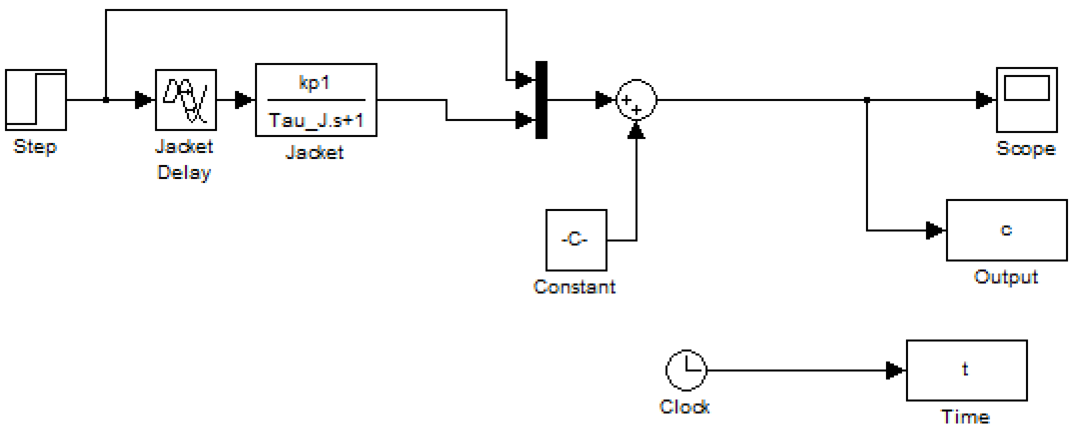


Figure 3. 17 Inner Loop Testing

Once all the best fit model parameters had been found the controllers for both the FOPDT and SOPDT models were designed using Simulink, it was decided to use a P controller for the secondary loop and a PI controller for the primary loop, a PI controller is not needed for the secondary loop as the integral action of the primary loop provides integral action for the process. When tuning controllers in cascade the inner loop must be tuned first, the closed loop system containing the secondary loop only is shown in figure 3.19.

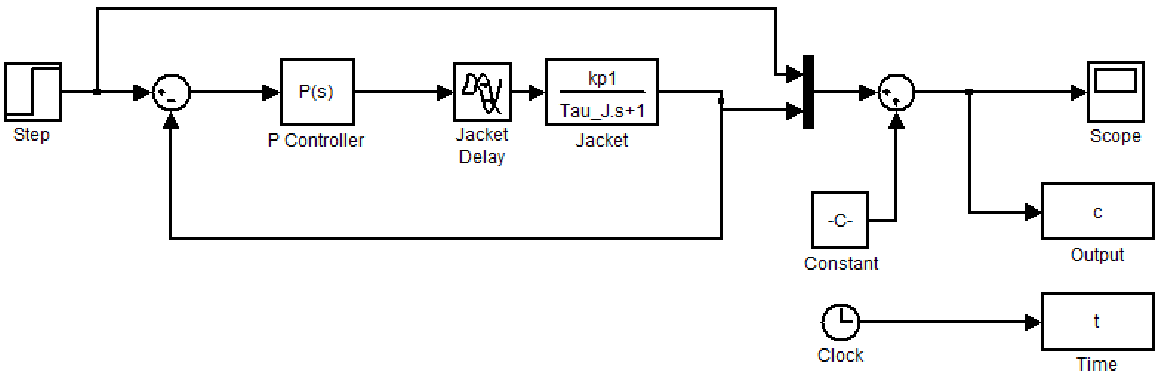


Figure 3. 18 Secondary Process Testing

The closed loop response from the secondary system is shown in figure 3.20 where it can be seen that the output does not reach the SP, this is because the controller is a proportional only controller and therefore the reference tracking is poor.

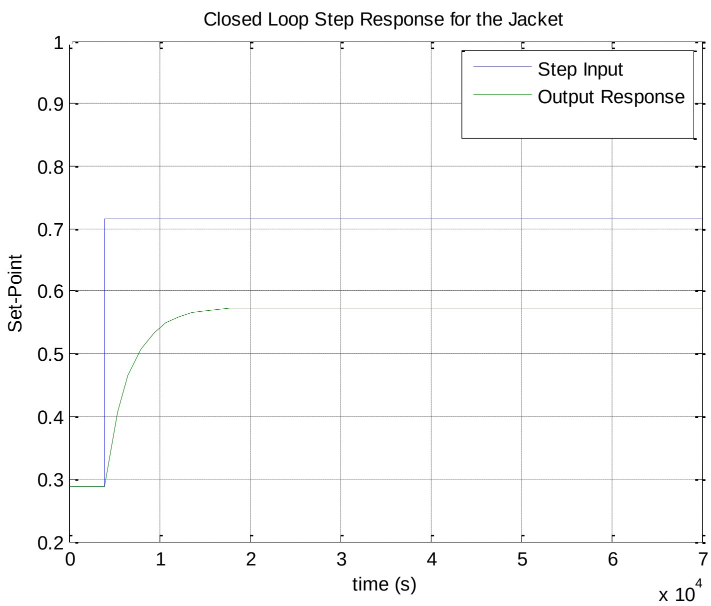


Figure 3. 19 Poor P Controller Reference Tracking

Next the tuned P controller was implemented in the SOPDT system, this is shown in figure 3.21., with the P controller now an intrinsic part of the system the primary PI controller can now be tuned using the Simulink PID controller tuning application.

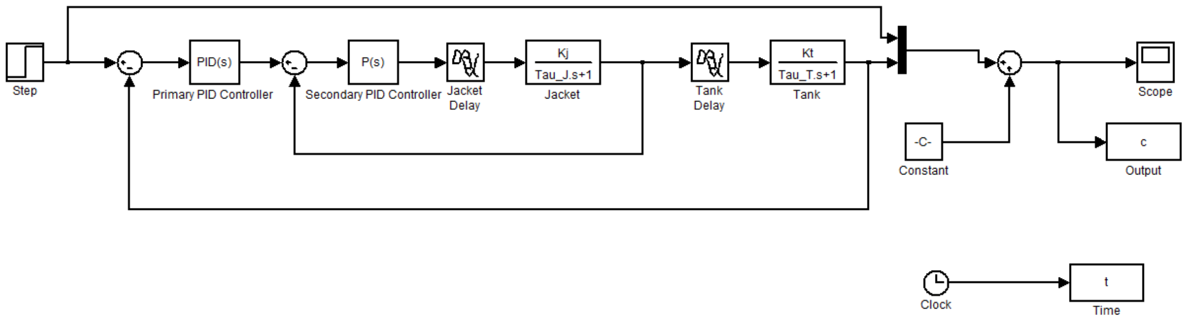


Figure 3. 20 SOPDT Testing

The output response from the system shown in figure 3.21 is shown below in figure 3.22.

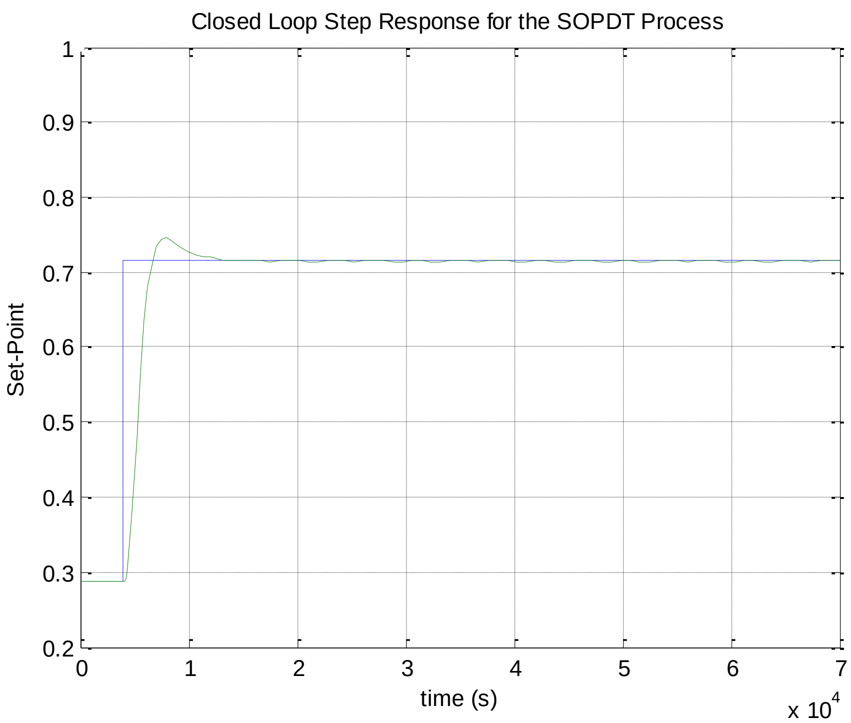


Figure 3. 21 SOPDT Model Step Response

The same process was then applied to the tuning of the FOPDT models, in this case however there is only a primary loop meaning that initially a P controller was introduced into the system tuned and then a PI controller was introduced to the system and then tuned.

3.7 Translating the Controller Algorithms to PLC code

Control theory when studied will be predominantly presented to the reader in the continuous time domain, this is because real world signals such as flow, current and in this case temperature are continuous time signals. On the other hand industrial controllers and their interfaces such as SCADA systems work with discrete signals, discrete signals may be created or obtained through the sampling of continuous time signals, and the result of this is that process controllers such as the PID controller must be implemented in discrete form.

Figure 3.23 below shows the process where an analog signal x(t) is sampled x(n), utilised in a digital algorithm which produces a digital output u(n), and then outputted in analog form to an actuator u(t).

Figure 3. 22 Continuous to Discrete Controller

The process shown in figure 3.24 is the same process that is involved in the control and automation of the pilot scale batch reactor in that both the jacket and the tank temperature transducers provide the analog input signals, these signals are then used in a discrete process control algorithm incorporating a primary and a secondary controller, the control algorithm then produces discrete output signals some of which are converted to analog form before being applied to both the PWM Flow Control Valve and the Phase Angle Controller which control the process heating and cooling respectively.

The primary controller used in this project is a PI controller, the secondary controller is a P controller, the method of attaining the discrete proportional term of a PI controller is identical to that of getting the proportional term of a P controller so only the derivation of the discrete PI controller will be now be shown.

$U(s) = K_P E(s) + \left(\frac{K_p}{s\tau_i}\right) E(s)$ PI controller in de-coupled industrial notation form

$U(s) = K_p E(s) + K_i E(s)$ PI controller in de-coupled textbook notation form

$U(s) = U_p(s) + U_i(s)$ Simplified notation

$u(t) = u_p(t) + u_i(t)$ Time domain simplified form of the PI controller

$u(n) = u_p(n) + u_i(n)$ Discrete simplified form of the PI controller

Proportional term

It can easily be seen by viewing the above PI controller equations that the Laplace transform for the Proportional term is $U_p(s) = K_p E(s)$, therefore the inverse Laplace transform is:

$\mathcal{L}^{-1}(\mathrm{U_p}(s)) = \mathcal{L}^{-1}(K_p E(s))$ giving $u_p(t) = K_p e(s)$ in the time domain,

which is the time domain representation of the proportional term of PI controller meaning the discrete proportional term is: $u_p(n) = K_p e(n)$

Integral term

Again it can easily be seen by viewing the PI controller equations that the integral term in the Laplace domain is $U_i(s) = K_i E(s)$, taking the inverse Laplace transform of this gives:

$\mathcal{L}^{-1}(U_i(s)) = \mathcal{L}^{-1}(K_i E(s))$ the time domain representation of the I term of the PI controller $u_i(t) = K_p \int_{t_0}^{t} e(\tau)d\tau$ and therefore $u_i(t-1) = K_p \int_{t_0}^{t-1} e(\tau)d\tau$

Therefore sampling at t=n gives the following discrete approximation of the continuous time controller:

$u_i(n) = K_p \int_{n0}^{n} e(\tau)d\tau$ and $u_i(n-1) = K_p \int_{n0}^{n-1} e(\tau)d\tau$

Therefore $u_i(n) = K_p \int_{n0}^{n} e(\tau)d\tau = K_i \int_{n0}^{n-1} e(\tau)d\tau + K_i \int_{n-1}^{n} e(\tau)d\tau$

The first term of the above expression has been shown to be $u_i(n-1)$

The second term can be approximated using the integral approximation using the sampling period T

$$\int_{n-1}^{n} e(\tau)d\tau = e(n) \times T$$

$K_i \int_{n-1}^{n} e(\tau)d\tau = K_i(e(n) \times T)$ therefore:

$u_i(n) = u_i(n-1) + K_i(e(n) \times T)$ which is the discrete implementation of the integral term of the PI controller.

4 System Derivation & Analysis

4.1 Deriving the jacket transfer function.

The time constant of the jacket was found using the two point method, the jacket PRC is shown in figure 4.1.

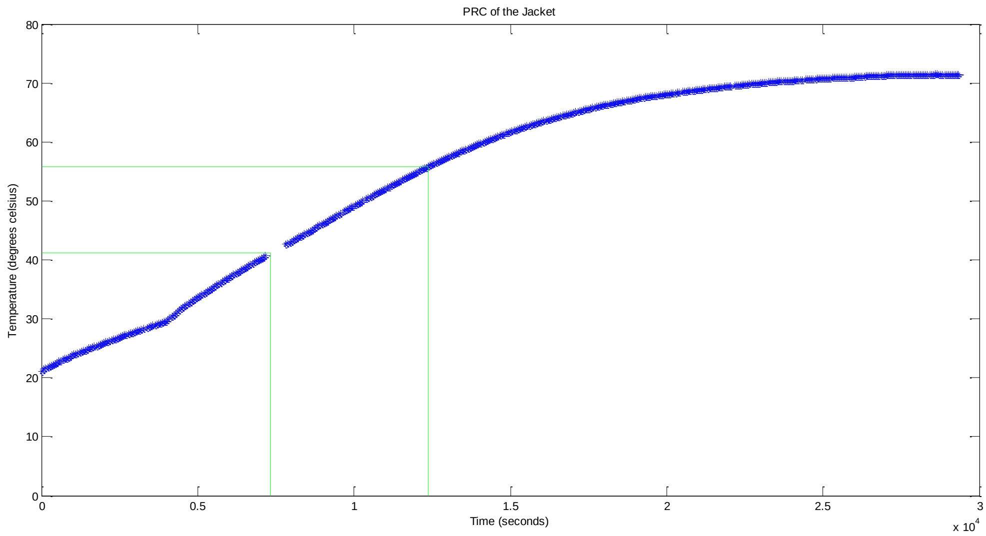


Figure 4. 1 Jacket PRC

The time accumulated before the Step Input was introduced was subtracted from the 28% and 63.21% points signified by the green plots in figure 4.1 to find the time constant. The Step Input was introduced to the jacket at 3990 seconds.

$$t2 = 12381.5 - 3990 = 8391.5 \text{ seconds}$$

$$t1 = 7329.5 - 3990 = 3339.5 \text{ seconds}$$

Calculating τ:

$$\tau = \frac{3}{2}(t_2 - t_1)$$

$$\tau = \frac{3}{2}(8391.5 - 3339.5) = \frac{3}{2}(5052)$$

$$\tau = 7578 \text{ seconds}$$

$$\tau = 126.3 \text{ minutes}$$

Finding the dead time of the jacket by inspection

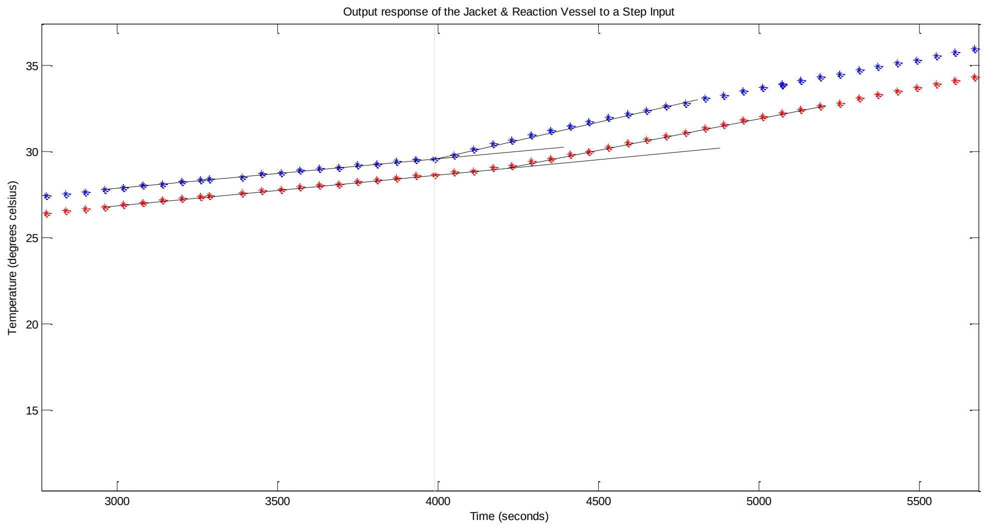


Figure 4. 2 Jacket Dead Time

From analysing the plot shown in figure 4.2 it can be seen that the jacket (the blue trend) exhibits an instantaneous reaction to the Step Input and that there is a delay of approximately four minutes between the introduction of the Step Input and the response from the tank.

The gain of the jacket was then found by comparing the developed model of the jacket with the jacket Process Reaction curve and was found to be 0.6996. This makes sense as the gain cannot be greater than 1 due to thermodynamic principles and that the system must not be adiabatic meaning that some of the energy used in the heating of the process is lost to its surroundings.

These results give a transfer function of $\dfrac{0.6996}{126.3s+1}$

4.2 Finding the time constant of the tank and the natural frequency and damping ratio of the system.

Analysis using trial and error approach

Analysis using graphically estimated dead time

Using Smiths method involves the analysis of the process output response. Note in the following calculations the dead time was found on a trial and error approach being reduced from 4 minutes down to 2 minutes, a value that correlated with the time constant calculated for the jacket.

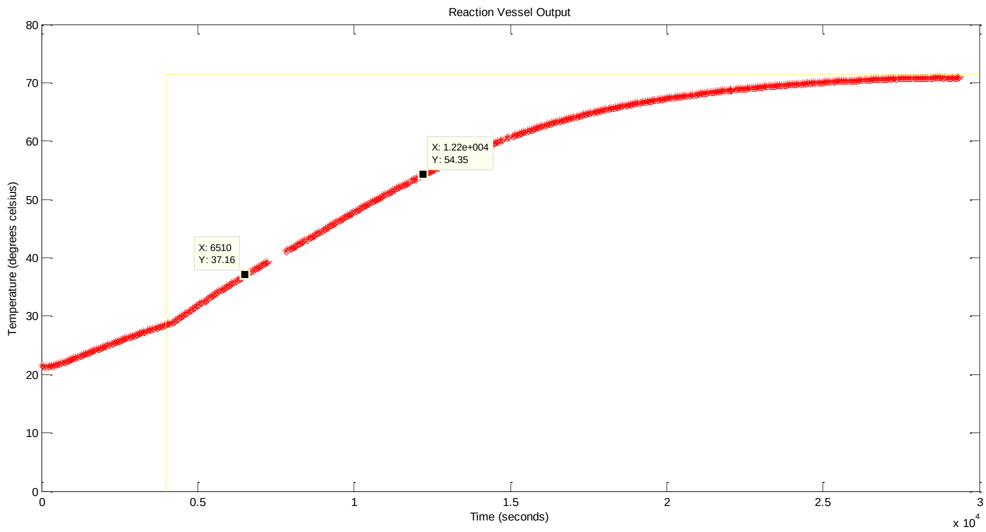


Figure 4. 3 Tank Step Response

Note the plot in figure 4.3 has a resolution of 1 minute, the calculations below use data that was sampled at 100 ms hence the small discrepancy in time between figure 4.3 and the calculations.

Ti=28.6788 @ 3990 secs =11:52

Tf= 71.5 at steady state

71.5 – 28.68= 42.82^{O}C

20% point = Ti + 42.82*0.2= 28.68 + 8.564 = 37.2445^{O}C occurs exactly at 6540 (6540 - 3990 = 2550)

60% point = Ti + 42.68*0.6= 28.68 + 25.61 = 54.288^{O}C occurs exactly at 12150 (12150 - 3990 = 8160)

$$t^{'} = t - \theta_d$$

$$t^{'} @ 20\% = x - 120$$

$t^{'} @ 20\% = 2550 - 120 = 2430$ $t^{'} @ 20\% = 2550 - 240 = 2310$

$$t^{'} @ 60\% = x - 120$$

$t^{'}\ @60\% = 8160 - 120 = 8040$

$t^{'}\ @60\% = 8160 - 240 = 7920$

$\frac{t_{20}}{t_{60}} = \frac{2430}{8040} = 0.302238806$

$\frac{t_{20}}{t_{60}} = \frac{2310}{7920} = 0.291\dot{6}$

From graphical interpretation $\frac{t_{60}}{\tau} = 4.\dot{1}\dot{8},\ \frac{8040}{\tau} = 4.\dot{1}\dot{8},\ \tau = 1922.61,\ \tau = 32.043\,\text{min}$

and zeta = 2.3545

From graphical interpretation $\frac{t_{60}}{\tau} = 4.772,\ \frac{7920}{\tau} = 4.772,\ \tau = 1659.68,\ \tau = 27.661\,\text{min}$

and zeta = 2.273

Note this analysis was done graphically using Smith's Method.

Using the results from Smith's method to find the Reaction Vessel Time Constant:

$$\tau^2 s^2 + 2\varsigma\tau s + 1 = (\tau_1 s + 1)(\tau_2 s + 1)$$

Expanding the RHS

$$\tau^2 s^2 + 2\varsigma\tau s + 1 = \tau_1\tau_2 s^2 + (\tau_1 + \tau_2)s + 1$$

Equating coefficients of s

$$\tau^2 = \tau_1\tau_2$$

$$2\varsigma\tau = \tau_1 + \tau_2$$

First of all looking at s^2

$$\tau_2 = \frac{\tau^2}{\tau_1}$$

$$\tau_2 = \frac{(32.043)^2}{126.3} = \frac{1026.75}{126.3} = 8.129\,\text{min} = 487.77\,\text{sec}$$

$$\tau_2 = \frac{(27.661)^2}{126.3} = \frac{765.131}{126.3} = 6.06\,\text{min} = 363.48\,\text{sec}$$

$$\varsigma = \frac{126.3 + 8.129}{2\sqrt{(126.3)(8.129)}} = \frac{133.58}{60.65} = 2.098$$ Graphical interpretation gave ζ=2.35

$$\varsigma = \frac{126.3 + 6.06}{2\sqrt{(126.3)(6.06)}} = \frac{132.36}{55.33} = 2.39$$ Graphical interpretation gave ζ=2.273e

Verifying calculations

$$\tau_1 = \frac{\tau}{\varsigma - \sqrt{\varsigma^2 - 1}} \quad (\varsigma \geq 1)$$

$$\tau_1 = \frac{32.043}{2.098 - \sqrt{(2.098)^2 - 1}} = 126.32 \quad (\varsigma \geq 1) \quad \tau_1 = \frac{27.661}{2.39 - \sqrt{(2.39)^2 - 1}} = 126.15 \quad (\varsigma \geq 1)$$

$$\tau_2 = \frac{\tau}{\varsigma - \sqrt{\varsigma^2 - 1}} \quad (\varsigma \geq 1)$$

$$\tau_2 = \frac{32.043}{2.098 + \sqrt{(2.098)^2 - 1}} = 8.128 \quad (\varsigma \geq 1) \quad \tau_2 = \frac{26.894}{3.04 + \sqrt{(3.04)^2 - 1}} = 4.55 \quad (\varsigma \geq 1)$$

4.3 Deriving the FOPDT transfer function

As was the case in using the two point method to find the time constant of the jacket the two point method was used to find the time constant of the process when the process was modelled as FOPDT. Again the time accumulated before the Step Input (3900 seconds) was subtracted from the 28% and 63.21% points signified by the green plots in figure 4.4 to find the time constant.

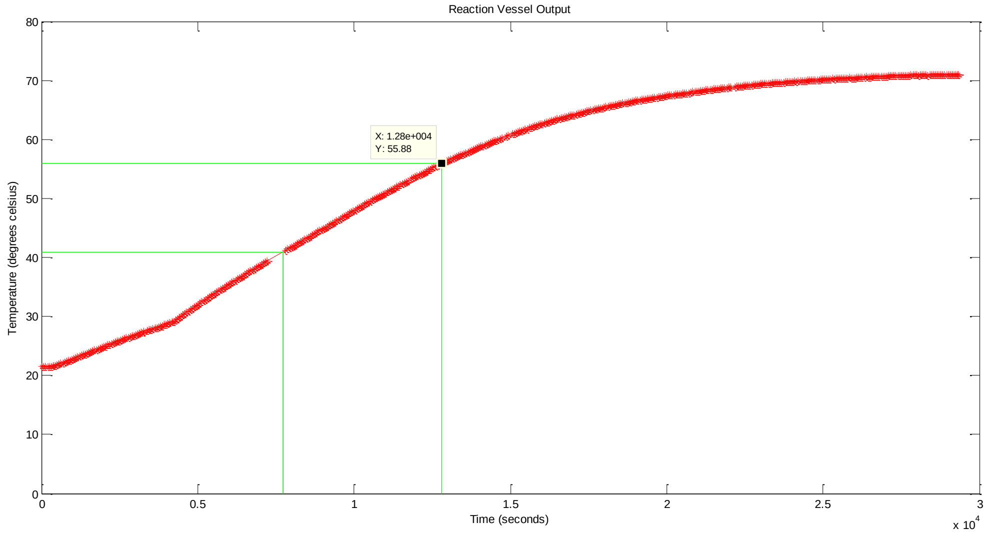


Figure 4. 4 Tank PRC Two Point Method

T_i =29.004 ^OC where T_i is the initial temperature

T_F = 71.504 ^OC where T_F is the Final temperature of the Process

$$\Delta T = T_F - T_i$$

$$\Delta T = 71.504^O C - 29.004^O C = 42.5^O C$$

$T_{28\%}$= T_i + 0.28ΔT

$$T_{28\%} = 29.004^O C + 0.28 \times 42.5^O C$$

$$T_{28\%} = 40.904^O C$$

$T_{63.21\%}$= T_i + 0.6321ΔT

$$T_{63.21\%} = 29.004^O C + 0.6321 \times 42.5^O C$$

$$T_{63.21\%} = 55.868^O C$$

$$t2 = 12798 - 3990 = 8808$$

$$t1 = 7715 - 3990 = 3725$$

Calculating τ:

$$\tau = \frac{3}{2}(8808 - 3725) = \frac{3}{2}(5083)$$

$$\tau = 7624.5 \text{ seconds}$$

$$\tau = 127.1 \text{minutes}$$

$$\frac{0.6996e^{-2400s}}{7625s + 1}$$

4.4 System Disturbance Response

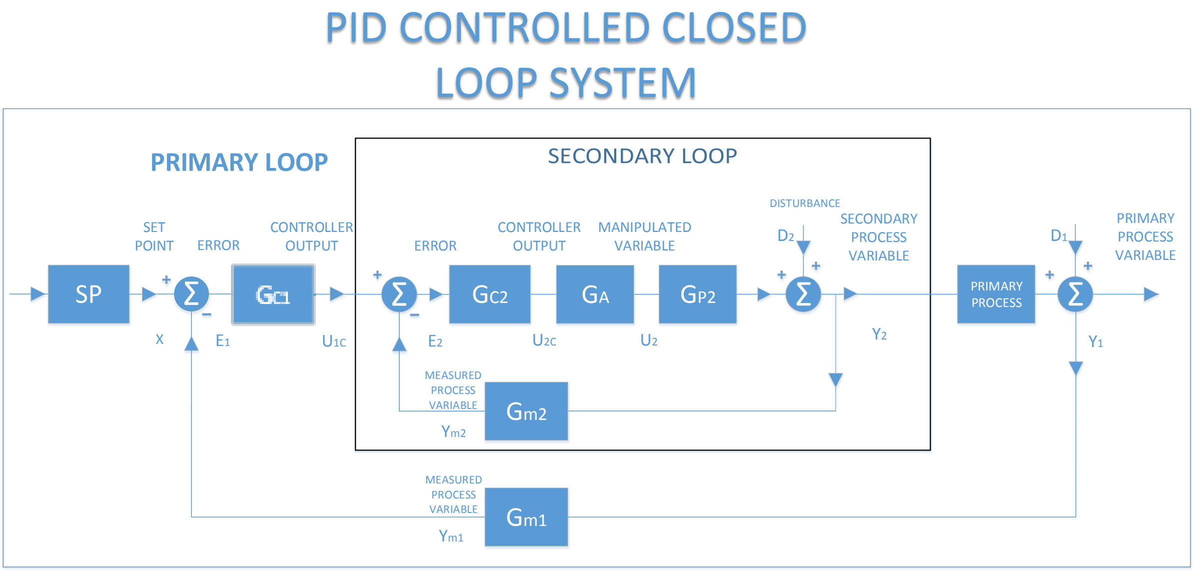


Figure 4. 5 Closed Loop System with Disturbances

Calculating a disturbance to the system at D2 when D1=0

$$Y_1 = G_{P1}Y_2$$

$$Y_2 = D_2 + G_{P2}G_AG_{C2}E_2$$

$$E_2 = U_{C1} - Y_{m2} = G_{C1}E_1 - G_{m2}Y_2$$

$$E_1 = -G_{m1}Y_1$$

Concentrating on the disturbance conditions and therefore FACTORING OUT ALL VARIABLES EXCEPT THOSE OF INTEREST being the output **Y1** to an input disturbance **D2**.

$$Y_1 = G_{P1}(D_2 + G_{P2}G_AG_{C2}E_2)$$

$$Y_1 = G_{P1}(D_2 + G_{P2}G_AG_{C2}(G_{C1}E_1 - G_{m2}Y_2))$$

$$Y_1 = G_{P1}(D_2 + G_{P2}G_AG_{C2}(G_{C1}(-G_{m1}Y_1) - G_{m2}Y_2))$$

MULTIPLYING OUT

$$Y_1 = G_{P1}D_2 + G_{P1}G_{P2}G_AG_{C2}(G_{C1}(-G_{m1}Y_1) - G_{m2}Y_2)$$

$$Y_1 = G_{P1}D_2 + G_{P1}G_{P2}G_AG_{C2}(-G_{C1}G_{m1}Y_1 - G_{m2}Y_2)$$

$$Y_1 = G_{P1}D_2 - G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P1}G_{P2}G_AG_{C2}G_{m2}Y_2$$

$$Y_1 = G_{P1}D_2 - G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P1}G_{P2}G_AG_{C2}G_{m2} \times \frac{Y_1}{G_{P1}}$$

$$Y_1 = G_{P1}D_2 - G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P2}G_AG_{C2}G_{m2}Y_1$$

$$Y_1 = G_{P1}D_2 - G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P2}G_AG_{C2}G_{m2}Y_1$$

$$Y_1 + G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 + G_{P2}G_AG_{C2}G_{m2}Y_1 = G_{P1}D_2$$

$$(1 + G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1} + G_{P2}G_AG_{C2}G_{m2})Y_1 = G_{P1}D_2$$

$$\frac{Y_1}{D_2} = \frac{G_{P1}}{\left(1 + G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1} + G_{P2}G_AG_{C2}G_{m2}\right)}$$

Calculating a disturbance to the system at D1 when D2=0

$$Y_1 = G_{P1}Y_2 + D_1$$

$$Y_2 = G_{P2}G_AG_{C2}E_2$$

$$E_2 = U_{C1} - Y_{m2} = G_{C1}E_1 - G_{m2}Y_2$$

$$E_1 = -G_{m1}Y_1$$

Concentrating on the disturbance conditions and therefore FACTORING OUT ALL VARIABLES EXCEPT THOSE OF INTEREST being the output **Y1** to an input disturbance **D1.**

$$Y_1 = G_{P1}\left(G_{P2}G_AG_{C2}E_2\right) + D_1$$

$$Y_1 = G_{P1}G_{P2}G_AG_{C2}E_2 + D_1$$

$$Y_1 = G_{P1}G_{P2}G_AG_{C2}\left(G_{C1}E_1 - G_{m2}Y_2\right) + D_1$$

$$Y_1 = G_{P1}G_{P2}G_AG_{C2}\left(G_{C1}\left(-G_{m1}Y_1\right) - G_{m2}Y_2\right) + D_1$$

$$Y_1 = G_{P1}G_{P2}G_AG_{C2}\left(-G_{C1}G_{m1}Y_1 - G_{m2}Y_2\right) + D_1$$

$$Y_1 = -G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P1}G_{P2}G_AG_{C2}G_{m2}Y_2 + D_1$$

$$Y_1 = -G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P1}G_{P2}G_AG_{C2}G_{m2} \times \frac{Y_1 - D_1}{G_{P1}} + D_1$$

$$Y_1 = -G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P2}G_AG_{C2}G_{m2}\left(Y_1 - D_1\right) + D_1$$

$$Y_1 = -G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 - G_{P2}G_AG_{C2}G_{m2}Y_1 + G_{P2}G_AG_{C2}G_{m2}D_1 + D_1$$

$$Y_1 + G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1}Y_1 + G_{P2}G_AG_{C2}G_{m2}Y_1 = D_1\left(G_{P2}G_AG_{C2}G_{m2} + 1\right)$$

$$Y_1\left(1 + G_{P1}G_{P2}G_AG_{C2}G_{C1}G_{m1} + G_{P2}G_AG_{C2}G_{m2}\right) = D_1\left(G_{P2}G_AG_{C2}G_{m2} + 1\right)$$

$$\frac{Y_1}{D_1} = \frac{G_{P2}G_A G_{C2}G_{m2} + 1}{\left(1 + G_{P1}G_{P2}G_A G_{C2}G_{C1}G_{m1} + G_{P2}G_A G_{C2}G_{m2}\right)}$$

4.5 Control Philosophy

The control system is required to regulate the temperature of a reaction vessel through the medium of a jacket. The temperature of the jacket is controlled through the process of heating and cooling via a cascaded controller architecture as has been shown in figure 4.5. The primary controller is a PI controller and the secondary controller is P controller which employs split range control to control two manipulated variables via a single process variable that being the output of the secondary controller; this is shown in figure 4.6.

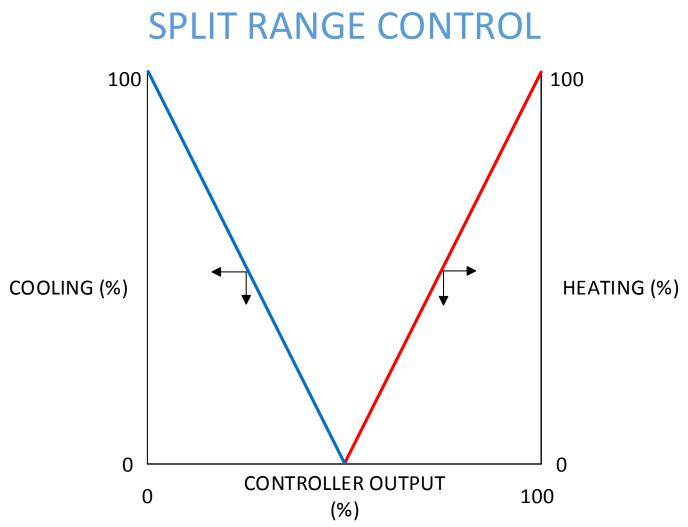


Figure 4. 6 Split Range Control

Automatic control, controller tuning and supervisory capabilities for the system are provided via a SCADA interface that reads from and writes to a control programme implemented in a hybrid ladder logic programme. The start up and automatic control of the process is initiated by a Boolean switch exclusive to the SCADA programme. Upon initiation of the programme all variables in the programme are reset to zero, this is achieved by utilising a status bit which only remains high for the first iteration of the rung of code the status bit is an intrinsic part of.

An E-stop the only physical button/switch interfaced with the control system is placed at all points in the code where the PLC is setting high outputs or internal bits that could energise any of the system actuators. A system On/Off Boolean switch sends the outputs high which power the contactor KM3 which must be energised for all the external power circuits to function. The contactor KM2 energises the pump and the relay R1 energises the agitator.

A Boolean switch Auto/Manual is set closed when in automatic mode, if this switch opens only the alarms and the manual facility for temperature control will be enabled. If the switch is closed full automatic control of the process is facilitated as-well as online manipulation of the controller gains.

A delay on timer with a NC switch in series with the timer is set high every six seconds therefore giving a sampling period of six seconds therefore updating all memory locations every six seconds.

The input analog signals are uploaded to the PLC via an A/D card, these signals have an offset resulting from the system instrumentation set up, this offset is removed and then scaled from DUs to ^{O}C.

The Set Point is written to the PLC from the SCADA system as is the primary and secondary controller gains.

The primary loop error is calculated by subtracting the primary process variable from the set point, then this error value is multiplied by each primary controller gain, the integrating output of the PI controller is multiplied by the sampling period to implement this controller in discrete form.

The integral term calculated on the previous iteration of the programme is added to the present I term. The present I term is then stored in a memory location to be used as the previous I term on the next programme iteration. The controller proportional and integral terms are then added to form the primary controller output.

The secondary loop error is calculated by subtracting the secondary process variable from the primary controller output, this error is then used to calculate the secondary controller output by multiplying the secondary controller error by the secondary controller gain, this value is then stored in a memory location.

The secondary controller output is calculated using the following formula:

$\frac{((SP - Pv_p)C_p - Pv_s)C_s}{((SP - Pv_p)C_p - Pv_s)C_s}$, it can be seen that the numerator and the denominator are identical, there is however a key difference in that the numerator values are dynamic and therefore updated every six seconds however the denominator values are updated only upon system start-up and when the set point is altered, this means that everytime the set point is altered the error is at 100%.

If the secondary controller output is between 100% and 50% the system heater is on, the zone control valve is closed meaning that water must flow through the heater. The return valve is closed and the flow control valve is closed. To achieve 100% output from the heater at 100% and 0% heater output at 50% the controller output is multiplied by 327.66 and 16384 DUs are subtracted from this value and sent to the analogue port to convert this signal to a 0-5V DC voltage to supply the PAC.

If the secondary controller output is between 50% and 0% the heater is off and the zone control valve bypasses the flow of water from the heater. The return valve is open and the flow control valve is open a certain percentage, the percentage modulation of the flow control valve is calculated by subtracting 50% from the controller output, multiplying by -1 to make the value positive and then multiplying by 655.32 DUs to give a DU range from 0-32766 DUs which is then sent to the analogue port which supplys the PWM flow control valve with a 0-10 V DC signal.

If the secondary controller output is greater than 100% the controller output is clamped at 100%, if the secondary controller output is less than 0% the controller output is clamped at 0%. Both of these actions prevent integral wind-up.

If the temperature rises above $100^{O}C$ the high level alarm is activated (this alarm must be acknowledged), this alarm brings the heating output to zero and the cooling output to 100%.

If the temperature falls below $0^{O}C$ the low level alarm is activated (this alarm must be acknowledged).

5. Analysis

5.1 Introduction

This section of the report is concerned with the performance of the FOPDT and SOPDT models of the process when interfaced with P and PI controllers, in the analysis of the model systems the same conditions that occurred during the successful step test are approximated and therefore a Step Input of approximately 42.83^{O}C is introduced to the systems under test.

Through analysis of the performance of the system using 6 key performance criteria a final model with associated controller architecture is found and various analysis tools are utilised to study this system in depth.

With the readily available access to tuning rules (see Dr Aidan O'Dwyers 'HANDBOOK OF PI AND PID CONTROLLER TUNING RULES' for an excellent resource) and other controller design methods available it has been decided that in this section that the system controllers will be designed using a range of methods and their performance evaluated.

Finally the disturbance rejection performance of the system will be analysed and a hypothetical situation where the tank and jacket sub-systems are swapped in the system architecture will also be examined.

5.2 Controller and System Performance Evaluation

Single Controller Architecture

Open Loop Ziegler Nichols method for Quarter Decay Ratio

A PI controller was tuned using the Zeigler Nichols tuning rules that were presented in section 2 of this report, these tuning rules are used on systems that are modelled as first order systems, therefore the derived FOPDT system was used to evaluate the controller designed using this method, this system is shown in figure 5.1.

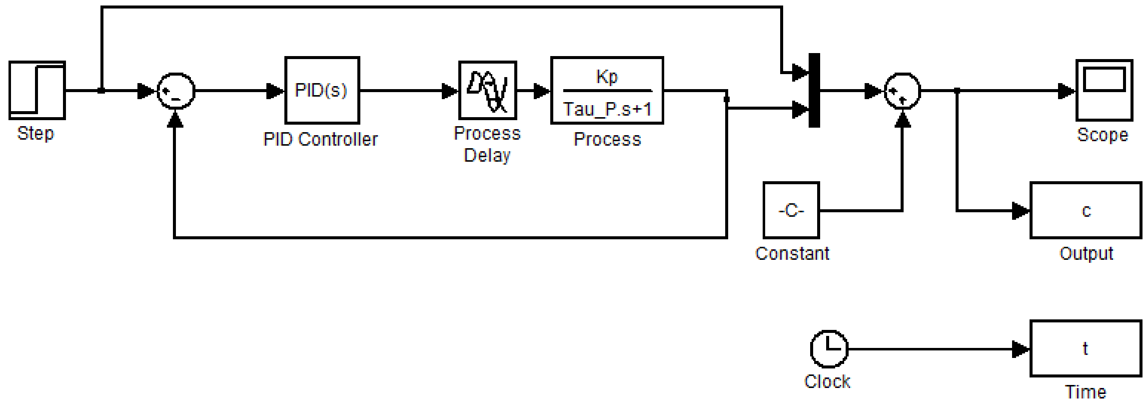


Figure 5. 1 FOPDT Simulink Circuit

Figure 5.2 shows the closed loop system output response to a step change in temperature of 42.83^{O}C, this is the Step Input that is applied to all the systems in this section of the report and therefore since the temperature at the point the Step Input was introduced to the system was 28.67^{O}C the set point is then 71.5^{O}C.

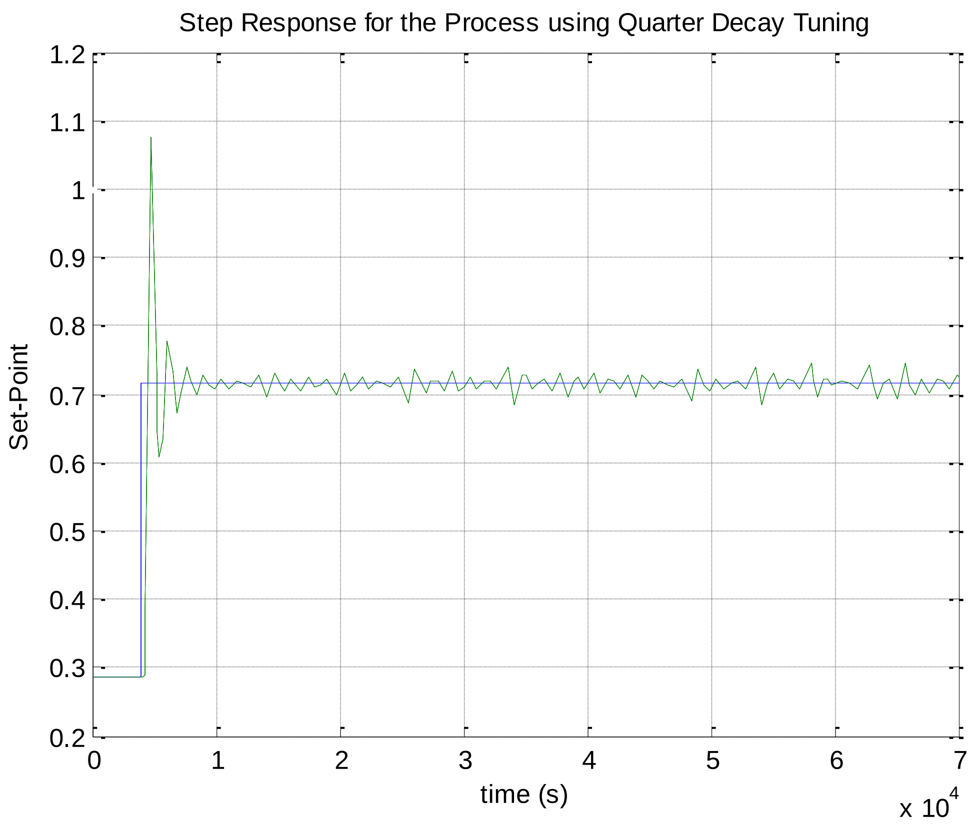


Figure 5. 2 Step Response Quarter Decay Tuning

By viewing figure 5.2 the time domain characteristics of the system using the PI Ziegler Nichols designed open loop controller can be observed. The most noticeable characteristic of the system response shown in figure 5.2 is the huge overshoot which is 84.26% of the final change in output, this overshoot however quickly decays and eventually the output settles to within +/- 6.5% of the set point. The system rise time is extremely quick at 447.01 seconds but this aggressive rise time manifests itself in the severe overshoot, finally the last time domain characteristic of interest is the system settling time, since the steady state error is +/- 6.5% this is taken as the point that the system has settled to within the aforementioned tolerance of the set point.

The transfer function for this system is: $\dfrac{28.59s + 0.03973}{7625s^2 + 29.59s + 0.03973}$

Figure 5.3 shows the Bode plot of the system shown in figure 5.1

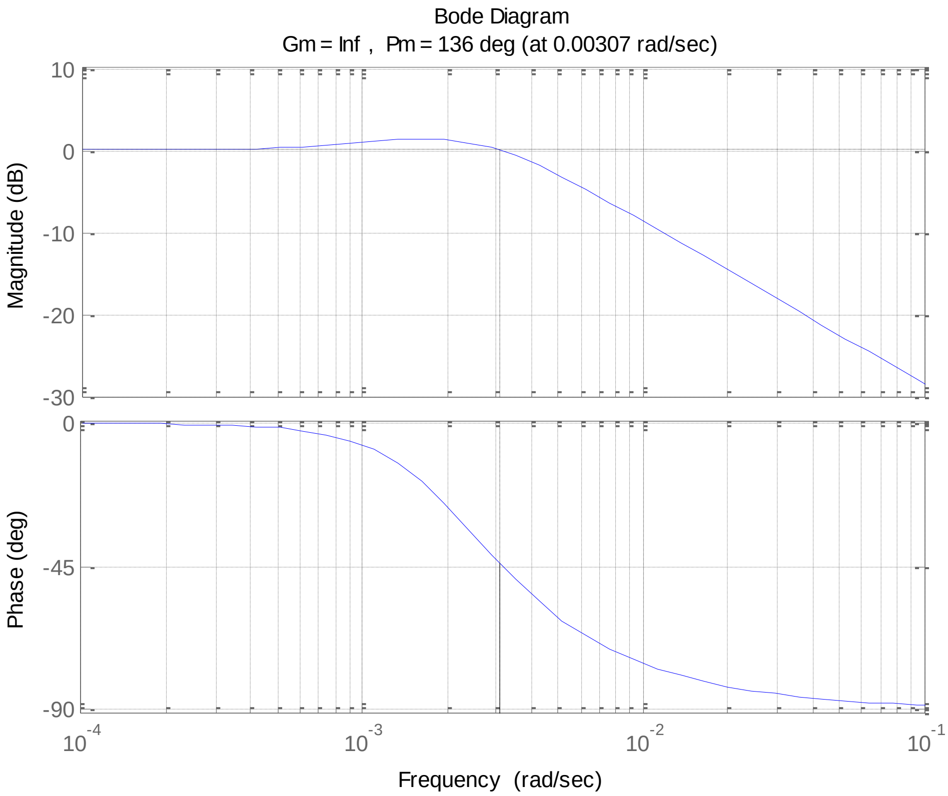


Figure 5. 3 Bode Plot Quarter Decay Tuning

Looking at the magnitude plot of figure 5.3 the system has a DC gain up to approximately 4.5 x 10^{-4} rad/sec, from 4.5 x 10^{-4} rad/sec to approximately 3 x 10^{-3} rad/sec, there will be some amplification of input signals with a maximum amplification of 1.4172 dBs in this range which equates to an amplification of 1.18. The roll off rate of the signal is 20dB per decade.

Looking at the phase plot of figure 5.3 there is no phase lag up to 10^{-4} rad/sec meaning that the output signal will follow the input signal in a true fashion up to this point, the phase change is at its most rapid between 10^{-3} and 10^{-2} radians per second and then from 10^{-2} the phase change is gradual.

The gain crossover frequency is located at 3.07×10^{-3} radians per second; a low crossover frequency indicates that the system response is slow. It can be seen in figure 5.3 that the phase does not cross -90^{O}, this is an important indicator to the stability of the system as the phase margin for all signals even the signals that have been attenuated by over 20dB have a phase margin of over 90^{O}.

Closed Loop Simulink Tuning

A single PI controller was tuned using Simulink PID tuner, it can be seen in figure 5.4 the system is second order.

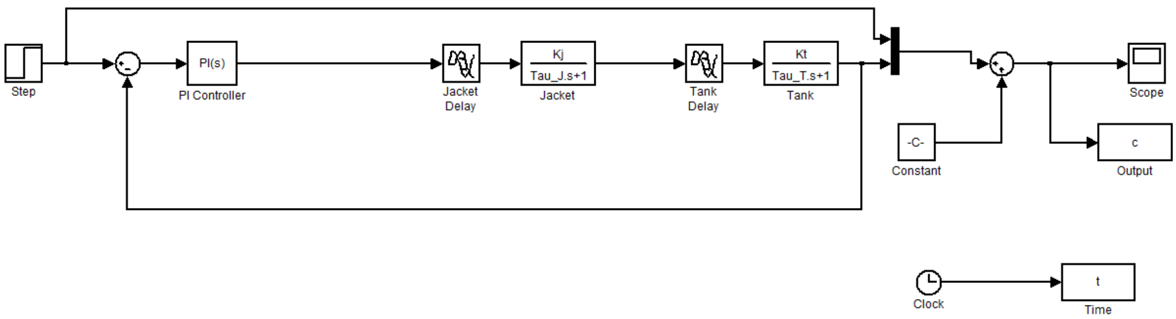


Figure 5. 4 SOPDT Simulink Circuit Single Controller

By viewing figure 5.4 the time domain characteristics of the system using the PI Simulink designed controller can be observed.

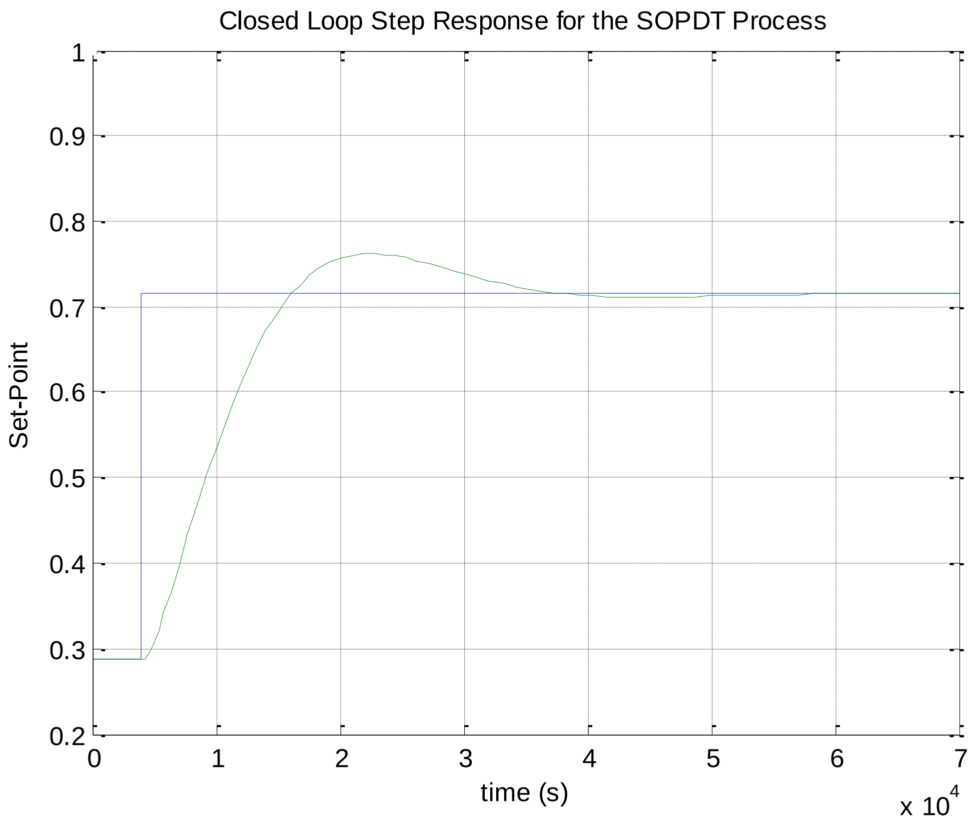


Figure 5. 5 Step Response to SOPDT Single Controller System

The most noticeable characteristics of the system response shown in figure 5.5 are the long rise time of 10076 seconds and the long settling time of 34182 seconds. The overshoot is 11.00% of the final change in output, this overshoot decays very slowly and eventually the output settles to within +0.05% of the set point.

Figure 5.6 shows the bode plot of the system shown in figure 5.4.

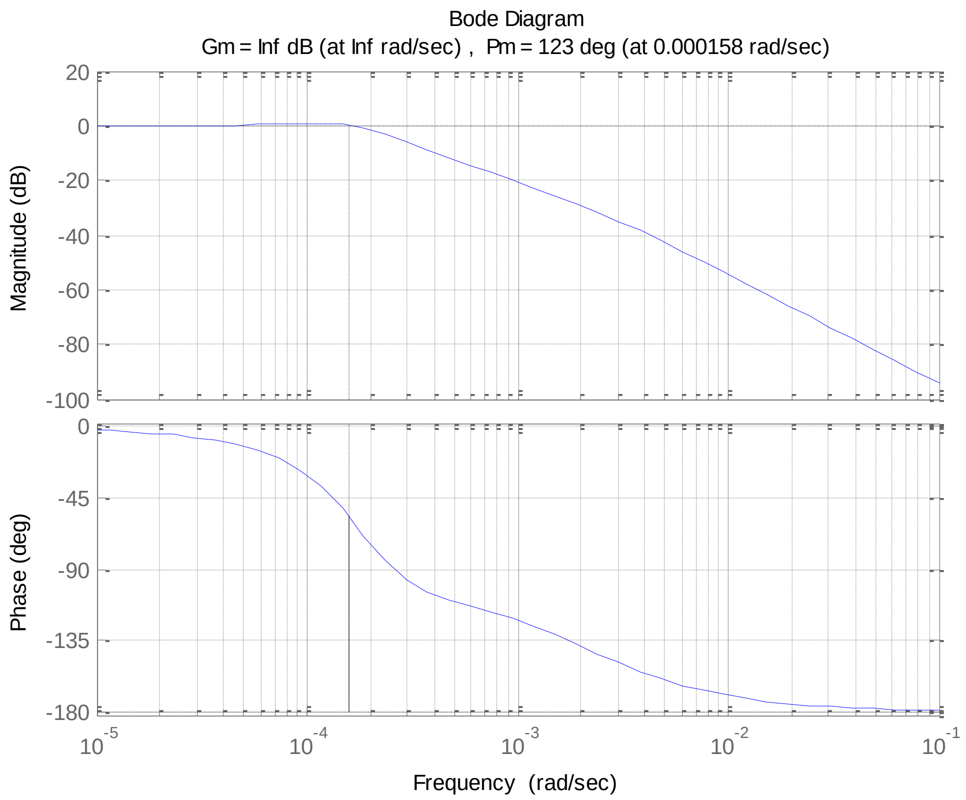


Figure 5. 6 Bode Plot Single Controller SOPDT

Looking at the magnitude plot of figure 5.6 the system has a DC gain up to approximately 8×10^{-5}rad/sec, from 8.5×10^{-5} rad/sec to approximately the cross over frequency at 1.58×10^{-4} rad/sec, there will be a negligible amount of signal amplification. The roll off rate is approximately 37dB per decade.

Looking at the phase plot of figure 5.6 there is a constant phase lag that is changing most rapidly at the gain cross over frequency meaning that the output signal will always have some lag relative to the input. The phase margin is 123^{O} and at no point does the gain cross over the phase crossover frequency of -180^{O}, as a result the system is stable.

The system transfer function is: $\dfrac{0.7166s + 232.4\times10^{-3}}{3.696\times10^{6}s^{3} + 8066s^{2} + 1.717s + 232.4\times10^{-3}}$

Cascade Controller Architecture

The system shown in figure 5.7 is the system used in the design of the following three controllers.

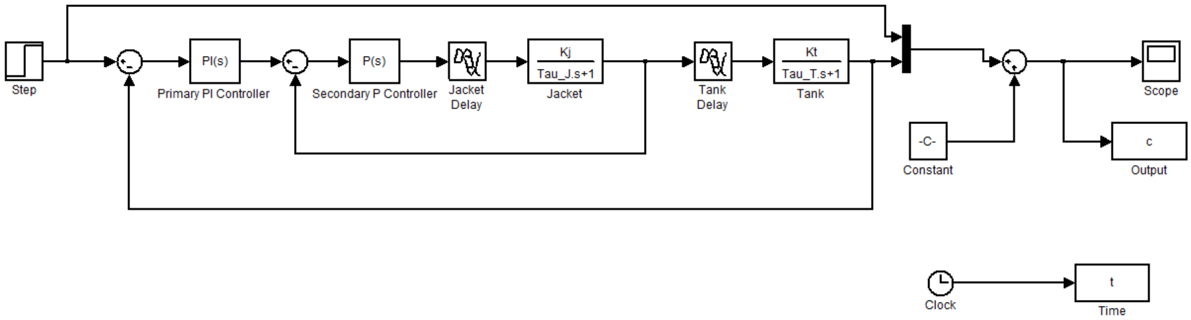


Figure 5. 7 Cascaded Controller Architecture Simulink

Closed Loop Ziegler Nichols method for Sustained Oscillation for a SOPDT process

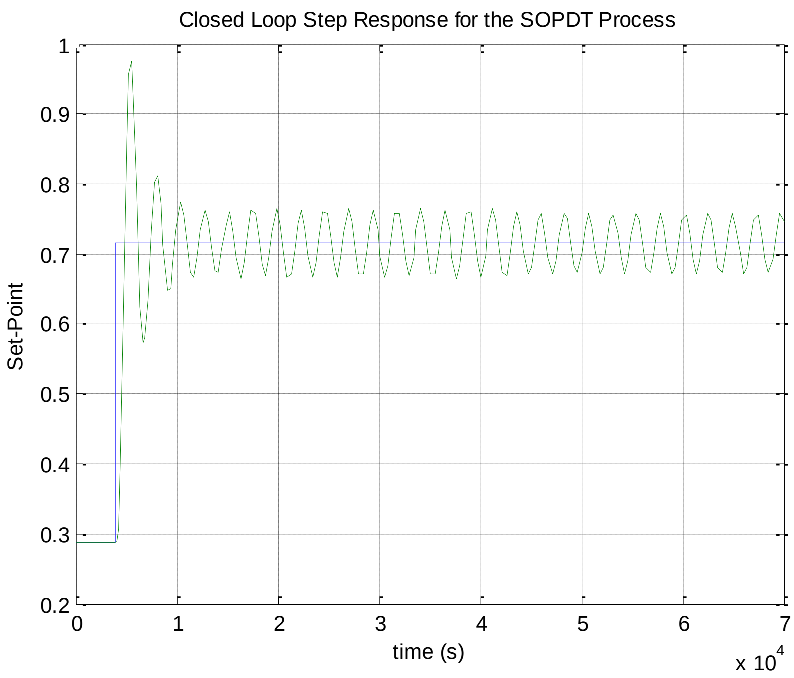


Figure 5. 8 Sustained Oscillations Step Response

By viewing figure 5.8 it can be seen that the rise time is small, there is a large overshoot of 59.5% and also that the system oscillates around the set point. The rise time of 837.82 seconds is aggressive and in stark contrast to the rise time found using the previous controller design of

10076 seconds. The system when using this controller design with sustained oscillation tuning achieves a steady state error of +/- 15.92% at 7854 seconds.

The system transfer function is: $\dfrac{19.88s+0.01435}{3.696\times10^{6}s^{3}+9143s^{2}+23.08s+0.01435}$

Figure 5.9 shows the bode plot of the system.

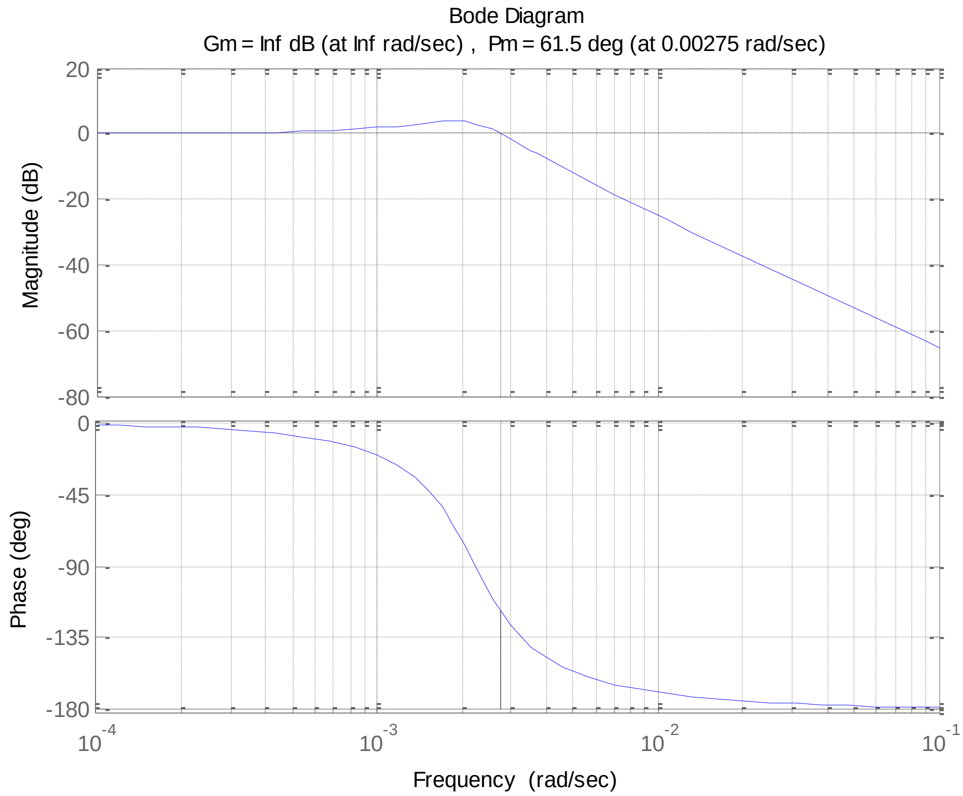


Figure 5. 9 Bode Plot Sustained Oscillations

Looking at the magnitude plot of figure 5.9 the system has a DC gain up to approximately 7 x 10^{-4}rad/sec, from 7 x 10^{-4} rad/sec to the cross over frequency at 2.75 x 10^{-3} rad/sec, there will be a maximum signal amplification of 3.4 dB which equates to a gain of approximately 1.48. The roll off rate is approximately 37dB per decade.

Looking at the phase plot of figure 5.9 the phase is changing most rapidly just before the gain cross over frequency, at the cut off frequency the output signal will have a lag of approximately -118^{O}. The phase crossover frequency of -180^{O} is never reached and therefore the system is stable and the gain margin is infinite.

Closed loop tuning of a SOPDT using Simulink

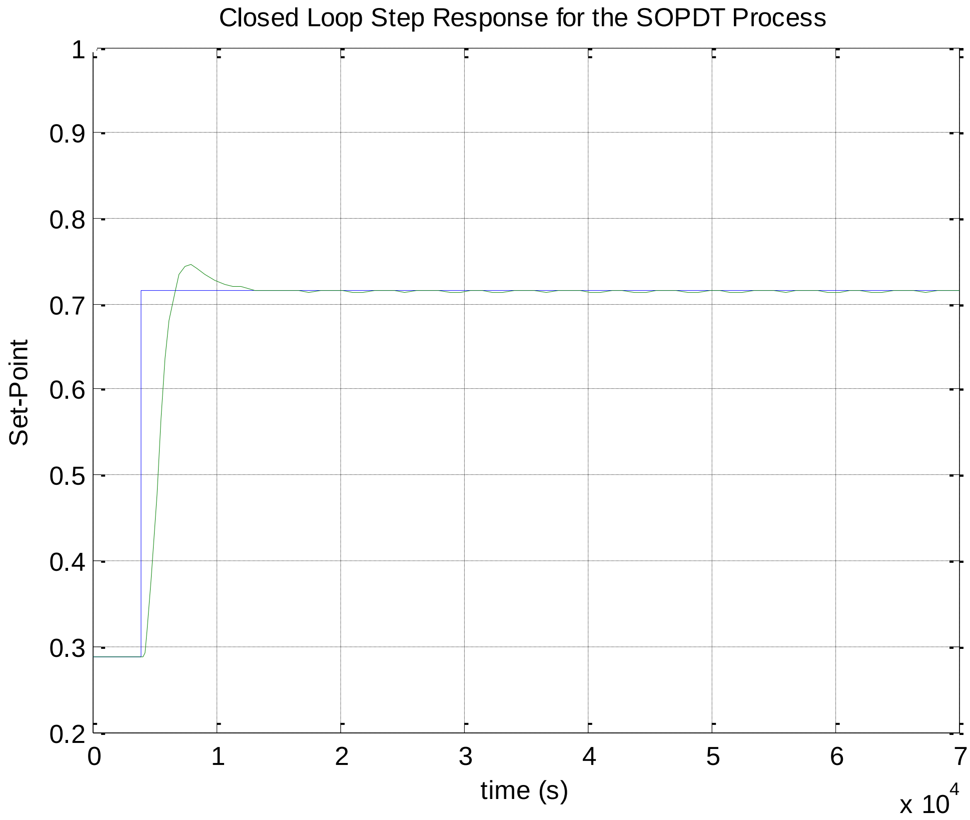


Figure 5. 10 Simulink Tuned Step Response

By viewing figure 5.10 it can be seen that the rise time is small, there is a overshoot of 7.07% which is relatively small to the overshoot of the other systems analysed and also that the system oscillates around the set point. The rise time of 2219.2 seconds is not nearly as aggressive as was found in the system using the sustained oscillation tuned controllers but then the overshoot of this system is approximately 1/8 of that of the previous system. This system with Simulink designed controllers achieves a steady state error of +/- 0.21% at 6486.8 seconds.

The system transfer function is: $\dfrac{5.423s + 0.002716}{3.696 \times 10^{6} s^{3} + 9062s^{2} + 8.465s + 0.002716}$

Figure 5.11 shows the bode plot of the system using the Simulink designed controllers.

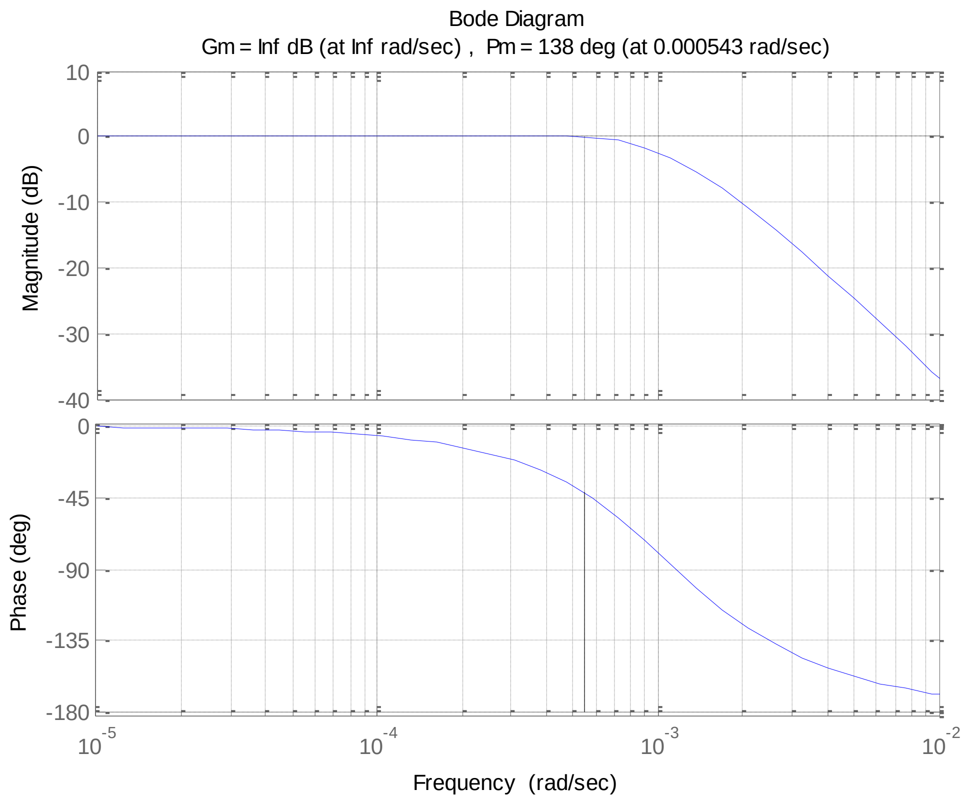


Figure 5. 11 Bode diagram Simulink Tuned SOPDT

Looking at the magnitude plot of figure 5.11 the system has a DC gain up to approximately 3 x 10^{-4}rad/sec, from 3 x 10^{-4} rad/sec to the cross over frequency at 5.43 x 10^{-4} rad/sec, there will be a maximum signal amplification of 0.214 dB which is negligible. The roll off rate is approximately 37dB per decade.

Looking at the phase plot of figure 5.11 the phase is changing most rapidly just after the gain cross over frequency however relative to the phase change seen in the system utilising controllers designed using the sustained oscillation method this change is very gradual. At the cut off frequency the output signal will have a lag of approximately 138^{O}. The phase crossover frequency of -180^{O} is never reached and therefore the system is stable and the gain margin is infinite.

The **closed loop controller design method using Matlab functions** and block diagram algebra yielded similar results to the Simulink design method and are shown in table 5.1 along with the results recorded from all the design methods investigated during this project.

Controller Design Method	Controller Architecture	Primary Controller		Secondary Controller		Performance Criteria	Results
Open Loop Ziegler Nichols method for Quarter Decay Response FOPDT	Single	PI	Kp=40. 874			RT (secs)	447.01
						%OS	84.26
						ST @+/- 6.5% SSE (secs)	3072
			Ki=0.05 676944			SSE	+/- 6.5%
						GM	In
						PM	136^{O} @ 0.00307 rads/sec
Closed Loop Simulink PID Tuning SOPDT	Single	PI	Kp= 1.0246			RT	10076
						%OS	11.00
						ST secs	34182
			Ki= 0.000 33232			%SSE	+0.05
						GM	Inf
						PM	123^{O} @ 0.000158 rads/sec
Closed Loop Ziegler Nichols method for Sustained Oscillation SOPDT	Cascaded	PI	Kp=9. 0	P	Kp=3.1 575	RT secs	837.82
						%OS	59.5
						ST @15.92% SSE	7854
			Ki=0.00 65			%SSE	15.92
						GM	Inf
						PM	61.5^{O} at @ 0.00275
Closed Loop Simulink PID Tuning SOPDT	Cascaded	PI	Kp=2.6 558	P	Kp=2.9 196	RT secs	2219.2
						%OS	7.07
						ST secs	6486.8
			Ki=0.00 133			%SSE	+/- 0.21
						GM	Inf
						PM	138^{O}
Closed Loop Tuning using Matlab functions SOPDT	Cascaded	PI	Kp=2.1 3165	P	Kp=2.0 426	RT secs	2826.7
						%OS	18.52
						ST	8800
			Ki=0.00 15			%SSE	+/-0.117
						GM	Inf
						PM	103^{O} @ 0.000635 rads/sec

Table 5.1

5.3 Disturbance Rejection

The red plot in figure 5.12 shows the disturbance rejection characteristics of the system utilising the single controller tuned using Simulink and with gains as shown in table 5.2, the blue plot is the cascaded controller architecture tuned using Simulink with gains also as shown in table 5.2.

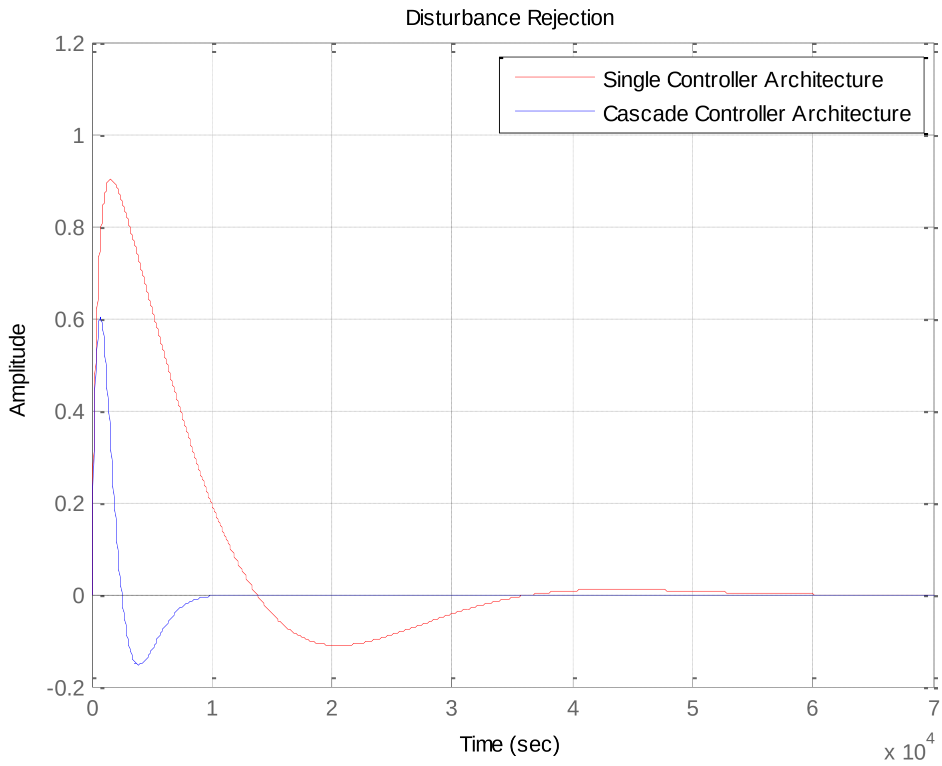


Figure 5. 12 Disturbance Rejection Single Vs Cascade

Table 5.2 displays the performance of the two controller architectures derived from the plot shown in figure 5.12.

Disturbance Rejection Performance			
Controller Architecture	Max disturbance response	Settling time	Steady State Error
Single Controller	+90.13%	7956	-0.645×10^{-3}
Cascaded Controller	+60.02%	32986	-1×10^{-3}

Table 5.2

Figure 5.13 presents the scenario where the jacket and tank sub-systems have been swapped in the system's architecture.

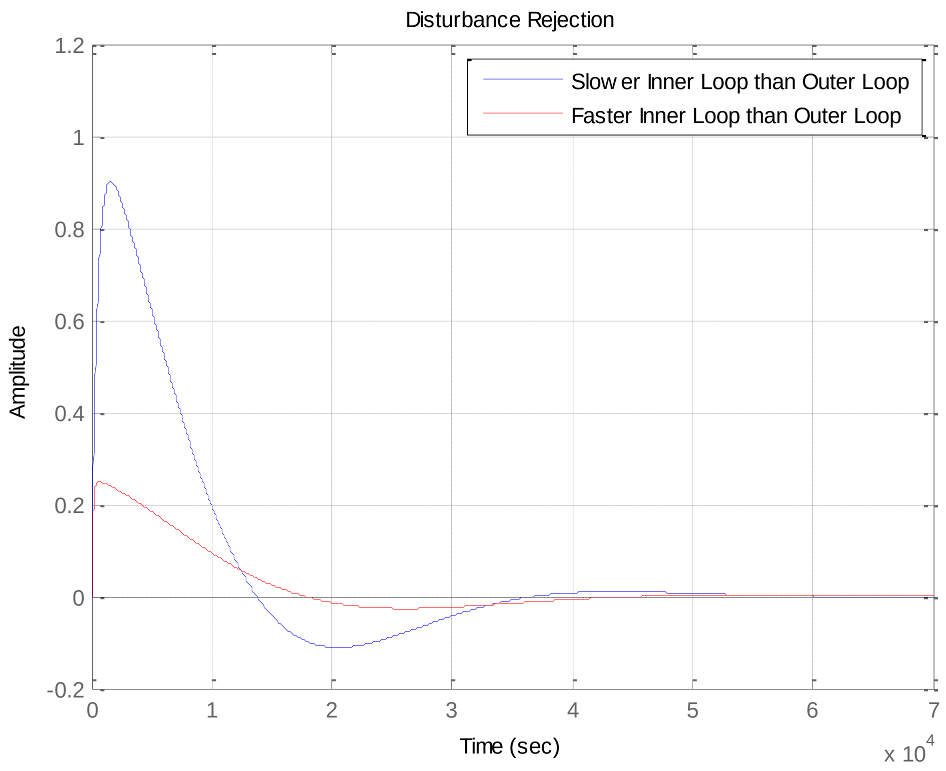


Figure 5. 13 Sub-systems Swapped Disturbance Rejection Performance

It can be seen in figure 5.13 that a system incorporating cascaded controllers and with a faster inner loop has a much better disturbance rejection performance than a system which doesn't, with a system that doesn't being the pilot scale batch reactor system. The system performance criteria derived from figure 5.13 are shown in table 5.3.

Disturbance Rejection Performance			
System	Max disturbance response	Settling time	Steady State Error
Slow Inner Loop	+60.02%	32986	-1×10^{-3}
Fast Inner Loop	+ 24.98%	32167	1.135×10^{-3}

Table 5.3

6. Conclusion

6.1 Introduction

This section of the report summarises the conclusions and objectively looks at the progress made. The objective for this project was to design, develop, implement and test the instrumentation and control for a pilot plant scale batch reactor with the two main objectives being the design of a control algorithm written using RSLogix Micro English and to facilitate the control of the system through a SCADA system therefore allowing for the automatic and manual control of the process. The control strategies outlined in the project brief were PID control, cascade control and split range control.

6.2 Project Issues

Initially there were issues with regard to recording the secondary process variable using the newest version of LabVIEW. This is because if you are running a 64 bit operating system there are two System DSN registers. One is 64 bit and the other is the legacy 32 bit. Microsoft has put these under the same name, so you have to run the 32 bit separately, from a directory. So when you load Kepware on the 64 bit machine it registers on the 32 bit register and then when you are searching for it, it appears not to be there because you are looking in the 64 bit register. It took some time to recognise this issue and delayed the procurement of test data.

Deriving the time constant of the tank ended up being the most challenging issue I was faced with during the project. Before the issue with KEPServerEX it was not possible to log data from the secondary process i.e. the jacket. Once this issue was resolved a step test was undertaken successfully and experimental data of the two processes primary and secondary was recorded. Using the experimental data deriving the transfer function of the jacket using the two point method was straightforward but deriving the transfer function of the tank was anything but. Initially I segmented the output from the jacket into a series of ramps and analysed the corresponding segments of the tank's output response, this method lead to the calculation of a time constant that varied depending on the section analysed and after a substantial amount of time and effort this method was abandoned. When searching the internet for the chart utilised in Smith's method or any documentation or analysis of using this method no results were returned, in fact the only place I have seen this method discussed was in the book "Process Dynamics and Control" (see bibliography), using the methods detailed in this book it was possible to find the time constant of the tank and therefore to model the system as SOPDT as well as FOPDT providing the opportunity to compare and contrast the performances of both systems.

6.3 Model Accuracy

Once the models of the two sub-systems were derived the process of obtaining the model that best fitted the experimental data was undertaken. Simulating the conditions that the step test was performed under, the best model turned out to be the SOPDT model of the system, however the SOPDT model developed using Smith's method turned out to be only a marginally better fit (to the recorded experimental data) than the FOPDT model derived using the two point method.

6.4 System Performance

Unfortunately at the point of writing I have not been able to implement my SCADA system and controller designs to the pilot scale batch reactor system, this will be done however before the project demonstration as the SCADA screens, tags and control algorithm have all been developed. Using the FOPDT and SOPDT system models a range of controller designs were tested and implemented on the FOPDT and SOPDT model systems. It was found through simulation that tuning rules like Zeigler Nichols for quarter amplitude decay for tuning a system open loop and Zeigler Nichols sustained oscillation method for closed loop tuning performed badly in comparison to the models utilising controllers developed using Matlab and in particular Simulink, this is not surprising however as these software packages perform the continued tuning required of the controllers that must be undertaken on a trial and error approach when using one of the aforementioned Zeigler Nichols methods, which only give a starting point from which to refine the controller tuning. One interesting outcome of these simulations was that the controllers designed for the second order system performed better than a controller designed for the FOPDT system even though most tuning rules are designed to utilise a FOPDT model, a model that is deemed appropriate to model most processes.

It was shown in the analysis section that when performance is evaluated against the six key performance criteria the cascaded controller architecture provides a level of performance that the single controller architecture just cannot compete with. With regard to the system's disturbance rejection performance the cascaded control architecture performs better than the single controller, this in fact is the main benefit of using controllers in cascade, however when reading up on cascaded controllers it was found that for this system to offer a substantially improved performance over single controller systems the inner loop must be much quicker than the outer loop. This theory was tested via simulations in the analysis section of the report and while having a cascaded controller architecture does offer improved performance over a single controller, it was found that when the tank and jacket sub-systems were swapped so that the tank was in the system inner loop, the jacket was placed in the outer loop and new controllers were designed that the theory holds correct and it is only with this type of system that the full benefit of cascade controllers can be realised.

6.5 Future Work

Unfortunately with the physical system set up textbook split range control is not possible, this is because there is only one modulating valve when in my opinion there should be two, although it should be mentioned that the heating phase which is from 100% to 50% of the secondary controller output works well apart from the fact that a linear relationship between the heater and the voltage/DUs does not exist but a significant portion of it could be linearised. Getting back to the cooling if there were two modulating valves then during the cooling phase the inflow rate of cold water would equal the outflow rate of the hot water, one possible strategy at the moment would be to have the return valve open from 50% to 0% and the modulating valve open 50% of its span at 50% controller output and increase this to 100% at 0% controller output. Another thought would be to implement a disturbance transmitter in the piping as close to the pump as possible and then employ feed-forward control, if a student next year was given a complete design brief of this project I am sure it is something that they could successfully achieve and it would make for a great project.

6.6 Summary

The main reason I choose this project was because in my opinion it was most practical project on offer and although this project has been highly time challenging and time consuming it has also been highly rewarding. Through undertaking this project I have learned about core project documentation which includes how to read and design a P&ID. I have vastly increased my knowledge of control systems and through system modelling, testing and controller design my Matlab and Simulink coding ability has also improved. Two other programming languages I have learned through the course of this project are how to programme using RSLogix Micro English and also in using the extremely powerful graphical programming language LabVIEW. Although at this point I have not implemented my control system on the pilot scale batch reactor by the time of my demonstration I will have, this will give me experience in using a real life SCADA system that I have designed and which could be invaluable to me on the next phase of my engineering career, that of the graduate electrical engineer.

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