SIMULATION AND OPTIMAL CONTROL OF CRUDE OIL SEPARATION PROCESS AT OFFSHORE FACILITIES TO IMPROVE EFFICIENCY OF OIL & CONDENSATE RECOVERY

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RESEARCH REPORT SUBMITTED TO THE FACULTY OF ELECTRICAL ENGINEERING UNIVERISITY OF MALAYA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF INDUSTRIAL ELECTRONICS AND CONTROL ENGINEERING

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Field of Study:

Instrumentation and Control

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Abstract – Crude oil separation process is the most crucial process in offshore production facilities in ensuring the well fluid is separated efficiently and persistently. Waxy crude or sluggish feed stream is the major disturbance that could cause operational issues and production loss due to process upset. The main objective of this research is to model offshore crude oil separation process and introduce state space control to optimize the control of total liquid and water level within the permissible range as well as to evaluate the effect of disturbances to the controls. This work presents two different modelling methods in developing three-phase separator model and application of state space control in optimizing the level control. The three-phase separator model is developed for liquid level and water phase level control using mathematical modelling and data driven modelling method via HYSYS. The mathematical model is based on two dynamic state equations representing the levels of the liquid and water and gas pressure with inflow and outflow dynamics. HYSS is used to simulate the three-separator dynamic process in a more realistic environment. The dynamic responses of liquid and water level to the command input of respective control valves are used to obtain data that is required to develop state space model. Application of state space (modern) control which are the feedback, feedforward control and integral action is investigated and evaluated in terms of its performance in controlling outflows of the separator in optimizing control of the separation process as well as in rejecting various disturbances such as slugging. In the end of this research, the simulation results show that state space control is able to control the crude oil separation process as desired while rejecting disturbances without causing process upsets. It was also found that by implementing integral action control, fast response time and zero steady state error can be achieved indicating that in the meantime, process fluctuation can be minimized and system response faster whereby it would help to improve the overall separation process efficiency.

Abstrak - Proses pemisahan minyak mentah adalah proses yang paling penting dalam industri luar pesisir dalam memastikan minyak mentah dipisahkan dengan cekap dan berterusan. Aliran minyak yang lembap adalah gangguan utama yang boleh menyebabkan masalah operasi dan kehilangan pengeluaran akibat proses gangguan. Objektif utama penyelidikan ini adalah untuk memodelkan proses pemisahan minyak mentah luar pesisir dan memperkenalkan "state space control" mengoptimumkan kawalan jumlah cecair dan paras air dalam julat yang dibenarkan dan juga untuk menilai kesan gangguan kepada kawalan. Kerja ini membentangkan dua kaedah pemodelan yang berbeza dalam membangunkan model pemisah tiga fasa dan penggunaan "state space control" dalam mengoptimumkan kawalan paras. Model pemisah tiga fasa dibangunkan untuk tahap tahap cecair dan paras air menggunakan pemodelan matematik dan kaedah pemodelan HYSYS. Model matematik didasarkan pada dua persamaan keadaan dinamik yang mewakili tahap tekanan cair dan air dan gas dengan aliran masuk dan keluar. HYSYS digunakan untuk mensimulasikan proses dinamik tiga pemisah dalam persekitaran yang lebih realistik. Tanggapan dinamik paras cecair dan air ke input masukan injap kawalan masing-masing digunakan untuk mendapatkan data yang diperlukan untuk membangunkan "state space model". "State space model" merupakan maklum balas, kawalan feedforward dan tindakan integral disiasat dan dinilai dari segi prestasinya dalam mengawal aliran keluar pemisah dalam mengoptimumkan kawalan proses pemisahan serta menolak pelbagai gangguan seperti slugging. Pada akhir kajian ini, hasil simulasi menunjukkan bahawa "state space model" dapat mengawal proses pemisahan minyak mentah seperti yang dikehendaki sambil menolak gangguan tanpa menyebabkan gangguan proses. Ia juga mendapati bahawa dengan melaksanakan kawalan tindakan integral, masa tindak balas yang cepat dan ralat keadaan sifar mantap dapat dicapai yang menunjukkan bahawa pada masa yang sama, turun naik proses dapat dikurangkan dan

respon sistem lebih cepat di mana ia dapat membantu meningkatkan kecekapan proses pemisahan keseluruhan.

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First and foremost, I would like to thank my research supervisor, Prof. Madya Ir. Dr. Mahidzal Bin Dahari at University of Malaya for his guidance and continuous support throughout my research. He is extremely helpful and patient in encouraging me to take up the challenge in an independent manner, but steered me to the right direction whenever he thought I need it. In addition, his Control & Automation class assignments was extremely helpful for research and provided me the knowledge and experience in doing this research.

Finally, I must express my very sincere gratitude to my parents, course-mates and friends for giving me continuous support and encouragement throughout my years of study and through the process of researching and writing this research paper. This accomplishment would not be possible without them. Thank you.

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Chapter 1: Introduction

Oil and gas industry is a major energy producer throughout the decades. It is expected that oil and gas sector would still dominant world energy market for the next two decades even though there has been increasing interest in the use of renewable energy in the recent years. Nevertheless, as oil and gas reserves become increasingly challenging and costly to explore and produce as well as due to the concern of environmental impacts, there is a need to apply optimization strategies with reference to other similar process industries which are more cost effective to ensure profitable operation of oil and gas production (Essen, Jansen & Hof, 2009).

Crude oil separation process is the most crucial process in offshore production facilities in ensuring the well fluid is separated efficiently and persistently. Inefficient or failure of the separation process could lead to serious cascading impacts on the downstream such as pipe blockages in which hydrates can form when water reacts with particular hydrocarbon components at low temperature and high pressure, equipment malfunction due to imperfect gas free liquid or liquid free gas and corrosive mixtures may form due to the reaction between acid gases (i.e. hydrogen sulphide and carbon dioxide) and water (Ahmed, Makwashi & Hameed, 2017).

This research discusses the offshore separation process, separator design and control strategies in section 2. A mathematical model and a HYSYS dynamic model are developed to model the three-phase separator in section 3. A state space control is designed and simulated in Simulink to control and demonstrate the separator behaviour during operation and process upsets in section 3. Lastly the simulation results are discussed in section 4 and summarized in section 5.

1.1. Objective

The main objective of this research is to model offshore crude oil separation process and introduce state space control to optimize the control of oil/water interface and oil level within the permissible range as well as to evaluate the effect of disturbances to the oil and oil/liquid interface levels. The disturbances are referred as fluctuation in inlet flow, surge due to other system upset, change in crude oil's viscosity or pour point and etc. An optimal separation process should achieve low oil in water ratio in discharge water, high purity of crude oil (degassing), eliminate liquid carry over to gas, efficient wet gas recovery, maintaining gas pressure set point for export, gas lift or even as fuel for gas turbine generator, and able to dampen disturbances like slugging. This is also beneficial in improving the reliability of the plant equipment e.g. pumps, compressors by reducing the breakdown frequency of equipment, eventually help to reduce the maintenance cost. This is due to the fact that the gas trapped inside liquid could lead to pump failure, whereas carry over liquid in gas could damage gas compressor or gas turbine.

Chapter 2: Literature Review

2.1. Offshore Separation Process

Well fluid from reservoir containing three phases mixture of liquid hydrocarbon (heavy oil and condensate), water and gas. Several separations stages are required to separate these phases into single phase mainly by density in offshore processing plant. First stage of separation is a rough separation of oil, water and gas in gravity from different wellhead at different location. The distance between the wellhead and separator and the pour point of the well characteristic would determine any fluctuations in liquid levels and gas pressure inside the separator. Thus, there is a need to develop effective control system to control liquid levels and gas pressure inside the three-phase separator in order to tackle the potential surge problem and ensure safe operation.

The overall separation process at offshore facility is illustrated in process flow diagram Appendix A. Firstly, the crude oil undergoes three-phase separation where oil, produced water and gas are separated in HP separator. Crude oil is then sent to LP separator for further separation. Refined crude is sent to storage tank and water goes to slope tank. Produced water is processed by hydrocyclone to further separate entrained oil from the produced water. Refined water is sent to degasser to further treat the water from hydrocarbon. Water that is within the limit of 40 ppm EDQ will be discharged overboard, while off-spec water will be sent to slope tank. All gases are sent to flare scrubber before being flared.

2.2. Three-phase Separator

The three-phase separator is designed and sized based on the well fluid characteristic in which the design may vary at different facilities. The first stage 3-phase HP separator receives fluids from the Slug Suppression System and liquid droplets from the HP

Scrubber. Incoming fluids from the Inlet Heater is processed whereby carry over gas is separated from the liquids and oil and water is separated. The separated gas is routed into the HP Scrubber and the oil and water is routed to the LP Separator and Produced Water System respectively. The HP Scrubber is designed primarily as a first stage 2-phase separator that receives fluids from the Slug Suppression System and flash gas from HP Separator. Incoming fluids from the Slug Suppression System is processed whereby carry over liquids are knocked out and is separated from the gas. Separated gas is routed to the Flare Scrubber and separated liquids are routed to the HP Separator via a downcomer pipe that extends below the low interface level of the HP Separator.

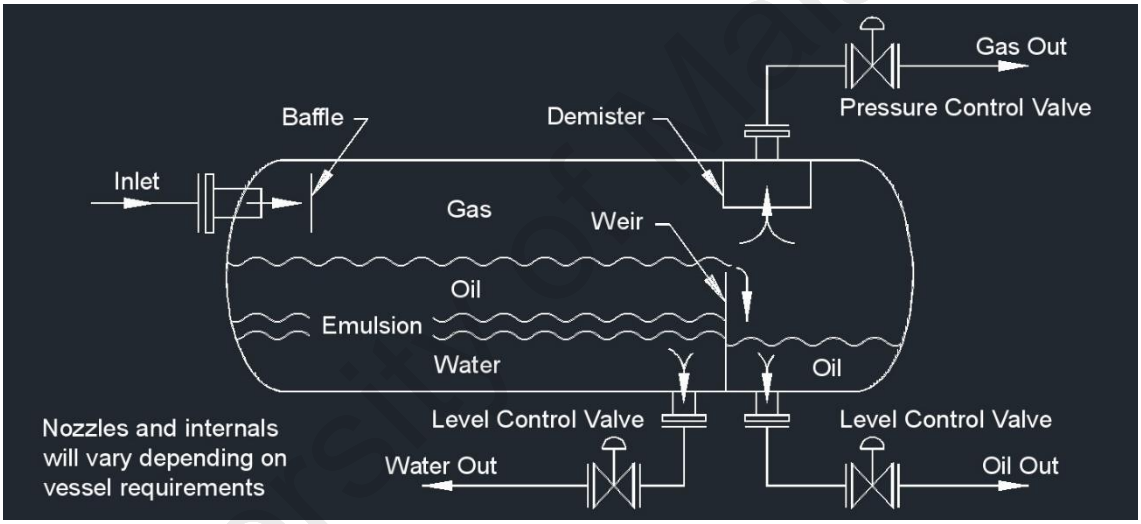


Figure 2.1: Three Phase Separator (Ratzlaff, 2016)

With reference to Figure 2.1, water is settled down at the bottom of the vessel due to gravity and oil 'waterfalls' over a weir located near the front of the vessel. The image at the right depicts a weir box. Oil & Water emulsion will form in between the oil and water phase, where the oil suspended in water or water suspended in oil. Since the level of fluid will not be higher than the weir, the oil which is lighter than water will float over the weir. The separation is governed by the residence time of the liquid, the liquids must have sufficient settling time for separation to complete as the surfacing of oil droplets takes time. Thus, the driving factor for this separation is residence time (Ratzlaff, 2016).

2.3. Control Philosophy

The level control philosophy in this system is to keep the liquid level within permissible range and able to dampen any potential surge input by controlling the level in accordance to the set point within a short duration without affecting the separation process performance as well as safety, for instance the occurrence of water or oil overflow or carry over, insufficient settling time for degassing and saturation, maintain vessel pressure constant and etc.

The main manipulated variables of this system are the two level control valves and a pressure control valve. The controlled variables is the oil/water interface level, oil level and pressure. There are 2 types of level control in three phase separator, namely liquid level control and interface level (level of the oil/water phase) control. The level sensor or can be a float level switch, capacitance probe, radar probe or diaphragm seal. Liquid level control is meant for controlling the total level of liquid by controlling the oil outlet flow via valve actuation in the field. As for interface level control, it is to ensure oil not being carried down the water leg or water not going down the oil leg. The interface level is mainly controlled by manipulating the water outlet flow via valve actuation at field.

In this particular case as shown in Figure 2.1, interface level controller is set with a set point of 0.50 m (50%) to automatically regulate in order to maintain desired level once the interface level reaches the set point. Oil outlet level controller is set with a set point of 1.38m (71%). Pressure controller is set with a set point of 5 to 10 barg.

Slugging is detected by either a rapid change in vessel level or vessel pressure. Slug disturbance control is designed to manage the disturbance due to slugging by throttling the inlet flow and flaring only as a last resort to avoid a trip.

2.3.1. State Space Control

State space control is introduced in this offshore separation process in order to maintain the oil and water levels equal to the set point despite various disturbances due to the fluctuations of inflow stream and gas pressure. Controlling the level equal to the set point is important not only to ensure separation efficiency but also to protect vessel from over-pressurization or over flow.

PID (proportional, integral and derivative) controller is the most common type of process controller being applied in oil & gas industry in which it uses feedback loop to correct the errors in between the setpoint and actual output by applying corrective signals. However, it comes with certain limitations, Firstly, PID controller does not support multiple inputs and multiple outputs (MIMO). The system will become very complex when more than one input or output. Secondly, PID controller also has limitation in controlling non-linear systems effectively as it is based on constant parameters (Collins, 2018).

State space model is an alternative control method to PID control. The significant difference between PID control and state space control is state space model includes the system's internal state, which is known as state variables. The state variables are to represent the system and response to any assigned inputs. However, for PID control, an observer is required to estimate the internal state of the system using measured inputs and outputs.

State space control is also known as modern control. It analyses differential equations, which represent the time domain of the system, in vector form with state variables. This allows the system can be evaluated via simplified matrix algebra. In addition, multiple-input and multiple-output systems can also be evaluated in such way. In the contrary, PID control is required to convert complex Laplace and Fourier transforms to time domain representation of the system in which is much more complex.

The main advantage of state space control over transfer function methods is its flexibility in wide range of systems: linear and non-linear; time-varying and time-invariant; single-input, single-output (SISO) and multiple-input, multiple-output (MIMO).

State space representation is formed by two equations. The state equation represents the connection between the current state and input to its future state of the system. The output equation represents the connection between the current state and input to its output.

The state space representation's state and output equations are as follows:

$$\dot{x} = Ax(t) + Bu(t) \tag{2.1}$$

$$y(t) = Cx(t) + Du(t) \tag{2.2}$$

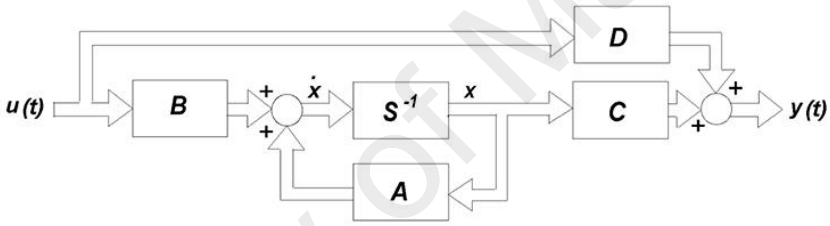


Figure 2.2: State space representation

2.3.2. PI controller tuning methods and Internal Model Control (IMC)

In 2010, Yang, Juhl, & Lohndorf simulated the three-phase separator using mathematical model and applied level control PI-type controller tuning by trial-and-error method, butterworth filter design method and IMC method. Their study shows that their current control system performance was significantly improved in terms of smooth water outflow rate with satisfactory water level control. They also concluded that IMC control has slightly better system performances than butterworth filter design. Lastly, they proposed to have future research onto the implementation of these control methods in the real system and using the outflow rate measurement for feedback control.

2.3.3. Dynamic mathematical modelling with PI controller

Sayda and Taylor (2007) developed dynamic model of the three-phase separator for each phase to study the steady state flows and separation behaviour for different operating conditions. They also designed simulation model of the oil production facility to evaluate the separator behaviour during normal operation and system upsets to validate their developed mathematical model. They have conducted an experiment onto PI controller in disturbance rejection whereby the PI controller is able to correct the upsets which was injected as disturbance; however, the separation efficiency was affected which resulted to the oil could not be separated and discharged to water. Their model not only address the dynamics of the process variables, but also the quality of the produced water and oil.

In 2017**,** Backi & Skogestad carried out related study onto the quality of produced water and oil to investigate the relationship in between the water levels and separation efficiency. They found that larger water levels could help to improve the quality of water outlet. In the contrary, the quality of the oil outlet is barely affected by the changes in the oil level. They also demonstrated better initial separation could result to better oil removal efficiency from water.

However, this is contradicting to the findings that the setpoints and disturbances have negligible effect onto the composition (oil-in-water and water-in-oil) for three-phase separator with control of pressure, oil level and water level when simulated in HYSYS (Tshitala 2001).

2.3.4. Model Predictive Control (MPC)

Hansen, Durdevic, Jepsen, & Yang (2018) carried out a research to study the feasibility and potential values of Model Predictive Control (MPC) in handling control problem due to fluctuation of inlet flow. The reasons for using MPC are: i) constraints to the control and process variables can be considered in the control design; ii) The predictive mechanism can help compensate some slow system dynamics; and iii) The MPC control can enable on-line estimation and optimization in a way it could be applied to various operating conditions and requirements than most “fixed” control methods.

2.3.5. State Observer

There are state variables which often cannot be measured, a state observer needs to be designed to estimate them. An observer is working when plant’s actual states and observer’s estimated states converge and approach zero after some time. And the system is said to be controlled when all states are approaching zero as time approaches infinity. The speed of convergence between actual state and the estimated state should be much faster than the transient response of the plant so that the controller will receive the estimated states instantaneously. The state estimation error, $e = y - \hat{y}$ should be small and reaching zero as time approaches infinity. The error between the outputs of the plant and the observer is fed back to the derivatives of the observer’s states. The system corrects to drive this error to zero. The transient response of observer with the addition of feedback should be quicker than the plant or controlled closed-loop system.

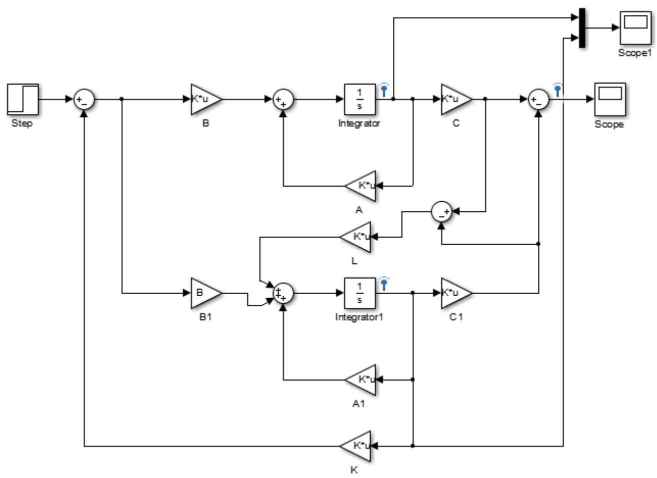


Figure 2.3: Observer

Chapter 3: Methodology

In this research, a wide range of knowledge, abilities and skills related to both process dynamics and control are required in order to design, analyse and control the offshore crude oil separation process. The methodology of this research consists of two main parts:

Part 1: Modelling

1. Mathematical and transfer function models of three-phase separation process are developed for both total liquid (oil plus water) and water level controls.
2. Dynamic models of the three-phase separation process in HYSYS are developed for both total liquid (oil plus water) and water level controls.
3. Stability and controllability of the models are checked in MATLAB.

Part 2: Control/Operation

4. All models are implemented in Matlab Simululink and apply state-space controls.
5. Open loop control system is simulated and observed its step responses.
6. Closed loop control system with full state feedback, feedforward again, integral action and disturbance rejection are simulated and evaluated its performance and disturbance rejection ability.

Two dynamics system modelling methods are used in this study namely mathematical modelling and data driven modelling (HYSYS simulation) as specified in Section 3.1 and 3.2. Transfer functions are then obtained from both models respectively. The transfer function can be used to analyse the process stability, controllability, dynamic responses and step responses. State space model are also converted from both transfer functions. Each state space model is based on single state variable which is liquid level or water phase level due to the controller two inputs and two outputs are both separated and individually controlled. This results in A, B, C and D matrix become (1x1) matrix.

3.1. Mathematical Modelling

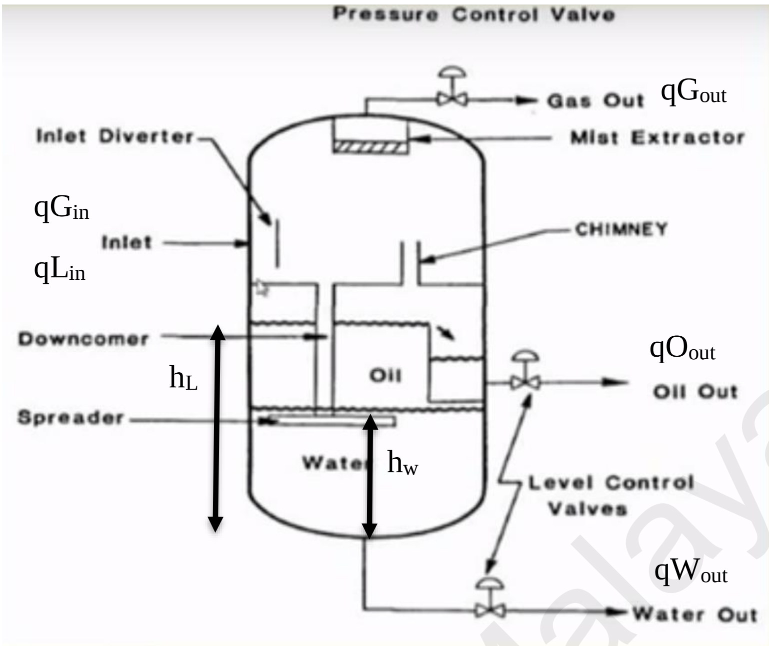


Figure 3.1: Schematic diagram of vertical three-phase separator

Figure 3.1 illustrates schematic of a horizontal three-phase separator with cross sectional view. It shows the different cross-sectional areas, liquid and water levels, the positions of the inlet and outlets as well as the dimensions of the separator. The dynamic part of the model is developed for the changes in total liquid level, water level and gas pressure.

Inlet liquid flow rate is assumed to be the only manipulated input for ease of modelling. In actual, the gas inlet flow rate should also be manipulated, however the focus of this study is level control, thus the gas pressure is assumed to be constant or with negligible pressure drop.

3.1.1. Mathematical Modelling – Total Liquid (Oil Plus Water) Level

Parameter values

$liquid\ level\ (oil + water), h = 2.1m$

$water\ outlet\ volumetric\ flowrate, q_w = 0.23\ m^3/min$

$$oil\ outlet\ volumetric\ flowrate, q_o = 1.61\ m^3/min$$

$$Separator\ Cross\ Sectional\ Area, A = \pi r^2 = \pi(1.22)^2 = 4.676m^2$$

The rate of change in liquid volume in separator can be defined as volumetric flow rates entering and leaving the three-phase separator. A material balance equation as follows can be formed by assuming the density of the inlet and outlet liquid as well as the accumulated liquid is constant.

$$\frac{dv}{dt} = A\frac{d(h)}{dt} = q_i - q_w - q_o \tag{3.1}$$

In order to obtain material balance model expressed in liquid level, some adjustments have been made.

$$\frac{dv}{dt} = A\frac{d(h)}{dt} = q_i - \frac{h}{R_1} - \frac{h}{R_2} = q_i - h\left(\frac{R_2 + R_1}{R_1 R_2}\right) \tag{3.2}$$

$$A\frac{d(h)}{dt} + hR' = q_i \tag{3.3}$$

$$A\frac{d(h - h_s)}{dt} + (h - h_s)R' = q_i - q_{is} \tag{3.4}$$

$$Let\ H = h - h_s\ and\ Q = q_i - q_{is}$$

$$A\frac{d(H)}{dt} + HR' = Q \tag{3.5}$$

$$Apply\ Laplace\ transform\ A\mathcal{L}\frac{dH}{dt} + R'\mathcal{L}\mathrm{H} = \mathcal{L}Q$$

$$A[sH(s) + H(s)] + R'H(s) = Q(s) \tag{3.6}$$

$$As\mathrm{H(s)} + R'H(s) = Q(s) \tag{3.7}$$

$$R'H(s)\left(\frac{1}{R}As + 1\right) = Q(s) \tag{3.8}$$

$$\frac{H(s)}{Q(s)} = \frac{1}{R'[\frac{1}{R'}As + 1]} = \frac{R_1R_2}{R_2 + R_1\left(\frac{R_1R_2}{R_2 + R_1}As + 1\right)} = \frac{K_p}{\tau s + 1} \qquad (3.9)$$

$$R_1 = \frac{h}{q_w} = \frac{2.1}{0.23} = 9.13$$

$$R_2 = \frac{h}{q_o} = \frac{2.1}{1.61} = 1.3$$

$$K_p = \frac{R_1R_2}{R_2 + R_1} = \frac{(9.13)(1.3)}{9.13 + 1.3} = 1.141$$

$$\tau = \frac{R_1R_2}{R_2 + R_1}A = 1.14(4.676) = 5.336$$

$$\frac{H(s)}{Q(s)} = \frac{K_p}{\tau s + 1} = \frac{1.141}{5.336s + 1}$$

The state space model is converted from the transfer function generated via mathematical modelling in section 3.1.1.

```
num = [1.141];
den = [5.336 1];
G = tf(num,den);
sys = ss(G);

A = [-0.1874];
B = [0.5];
C =[0.4277];
D = [0];
p1 = -1;
K = place(A,B,[p1]);
```

The pole can be calculated using "pole" command. The stability of the system can be checked using the command below.

```
>> pole(G)

ans =

   -0.1874

>> isstable(G)

ans =

     1

>> Matrix_contr=ctrb(A,B)

Matrix_contr =

    0.5000

>> rank(Matrix_contr)

ans =

     1
```

The negative value of the pole indicates the system is stable, whereas the rank of 1 for stability and controllability shows that the system is stable and controllable respectively.

3.1.2. Mathematical Modelling – Water Phase Level

$water\ level, h = 1.05m$

$water\ outlet\ volumetric\ flowrate, q_o = 0.23m^3/min$

$Area, A = \pi r^2 = \pi(1.22)^2 = 4.676m^2$

$$\frac{dv}{dt} = A\frac{d(h)}{dt} = q_i - q_o \tag{3.10}$$

$$R = \frac{h}{q_o}$$

$$A\frac{d(h)}{dt} + \frac{h}{R} = q_i \tag{3.11}$$

$$A\frac{d(h - h_s)}{dt} + \frac{h - h_s}{R} = q_i - q_{is} \tag{3.12}$$

$$Let\ H = h - h_s\ and\ Q = q_i - q_{is}$$

$$A\frac{d(H)}{dt}+\frac{H}{R}=Q \tag{3.13}$$

$$Apply\ Laplace\ transform\ A\mathcal{L}\frac{dH}{dt}+\frac{1}{R}\mathcal{L}\mathrm{H}=\mathcal{L}Q$$

$$A[sH(s)+H(s)]+\frac{H(s)}{R}=Q(s) \tag{3.14}$$

$$As\mathrm{H(s)}+\frac{H(s)}{R}=Q(s) \tag{3.15}$$

$$H(s)\left(As+\frac{1}{R}\right)=Q(s) \tag{3.16}$$

$$\frac{H(s)}{Q(s)}=\frac{R}{ARs+1}=\frac{K_p}{\tau s+1} \tag{3.17}$$

$$R=\frac{h}{q_o}=\frac{1.05}{0.23}=4.565$$

$$\tau=AR=\ 4.676(4.565)=21.346$$

$$\frac{H(s)}{Q(s)}=\frac{K_p}{\tau s+1}=\frac{4.565}{21.346s+1}$$

The state space model is converted from the transfer function generated via mathematical modelling in section 3.1.2.

```
num = [4.565];
den = [21.346 1];
G = tf(num,den);
sys = ss(G);

A = [-0.04685];
B = [0.5];
C =[0.4277];
D = [0];
p1 = -1;
K = place(A,B,[p1]);
```

The open loop system (without any control) is analysed whether it is stable. The pole can be calculated using "pole" command. The stability of the system can be checked using the command below.

```
G =

     4.565
  -----------
  21.35 s + 1

Continuous-time transfer function.

>> sys

sys =

  a =
            x1
   x1  -0.04685

  b =
        u1
   x1  0.5

  c =
          x1
   y1  0.4277

  d =
       u1
   y1   0

Continuous-time state-space model.
```

```
>> pole(G)

ans =

   -0.0468

>> isstable(G)

ans =

     1

>> Matrix_contr=ctrb(A,B)

Matrix_contr =

    0.5000

>> rank(Matrix_contr)

ans =

     1
```

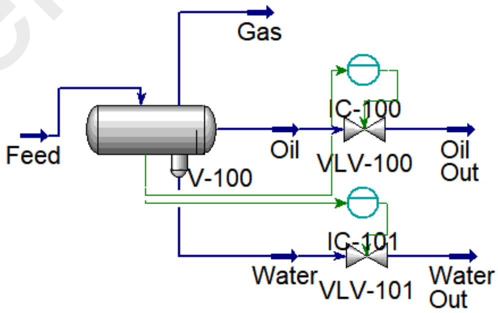
This shows the open loop system is stable and controllable. The negative value of the pole indicates the system is stable, whereas the rank of 1 for stability and controllability shows that is the system is stable and controllable respectively.

3.2. Data Driven Modelling (HYSYS Simulation)

The three-phase separation process is designed, simulated and studied in a more realistic approach by using HYSYS (as shown in Figure 3.2) for gathering dynamic simulation data, and is connected with MATLAB for identification and control. The process parameters and design specifications are illustrated in Figure 3.2 and Appendix A & B.

Both control valves are sized and the open loop relationship between their control signals for valve actuation (manipulated variables) and the liquid level response (controlled variables) are studied to develop transfer function or state space. This can be achieved by running the process simulation on HYSYS to model the dynamic process in order to obtain the required data for dynamic system identification. Transfer function or state space is obtained so as to implement modern control for process control optimization. The disturbance Q_{in} is also injected to test the system robustness.

MATLAB System Identification Toolbox is used for constructing the mathematical models of dynamic systems from the HYSYS input-output data to generate transfer function or state space.



V-100		
Separator Type	Three Phase	
Vessel Temperature	65.00	C
Vessel Pressure	1000	kPa
Vapour Molar Flow	1429	kgmole/h
Liquid Molar Flow	209.5	kgmole/h
Aqueous Level	0.1358	m
Liquid Level	1.685	m

Figure 3.2: HYSYS simulation dynamic model

3.2.1. HYSYS Modelling – Total Liquid (Oil Plus Water) Level

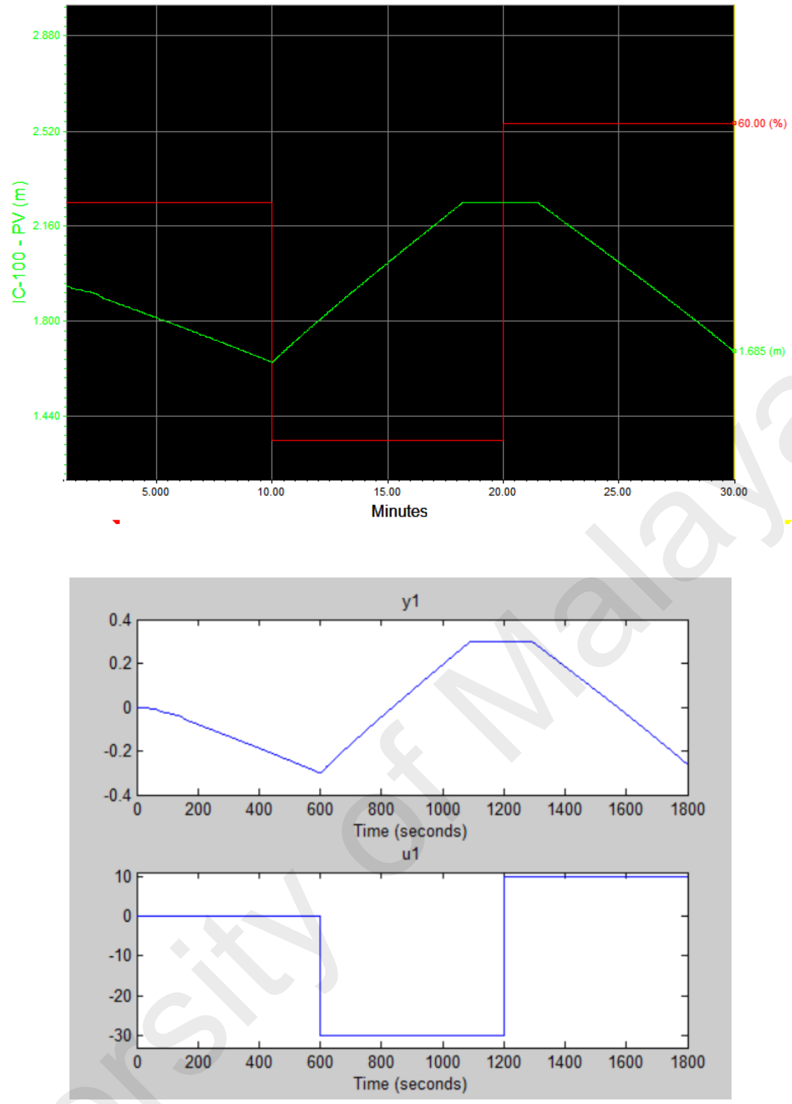


Figure 3.3: Simulation input-output data (control signal and liquid level) generated from HYSYS

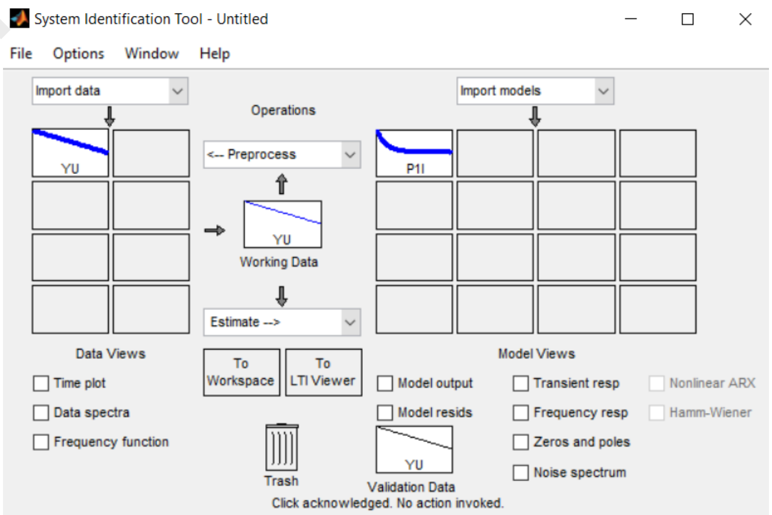


Figure 3.4: System Identification Tool to generate state space model for liquid level state variable

```
A =
          x1
 x1  0.0001191
B =
           u1
 x1  -5.074e-06
C =
       x1
 y1  7.662
D =
     u1
 y1   0
```

The state space model is obtained from HYSYS simulation data via MATLAB System Identification Toolbox in Session 3.2.1.

```
A = [0.0001191];
B = [-5.07e-06];
C = [7.662];
D = 0;
[b,a]=ss2tf(A,B,C,D);
G=tf(b,a);
p1 = -1;
K = place(A,B,[p1]);
```

The pole can be calculated using "pole" command. The stability of the system can be checked using the command below.

```
>> isstable(G)

ans =

     0

>> pole(G)

ans =

   1.1910e-04
```

Positive pole value and rank of 0 for stability indicate the system is unstable.

```
>> Matrix_contr = ctrb(A,B)

Matrix_contr =

  -5.0700e-06

>> rank(Matrix_contr)

ans =

     1
```

Nonetheless, rank of 1 for controllability indicates the system is controllable.

3.2.2. HYSYS Modelling – Water Phase Level

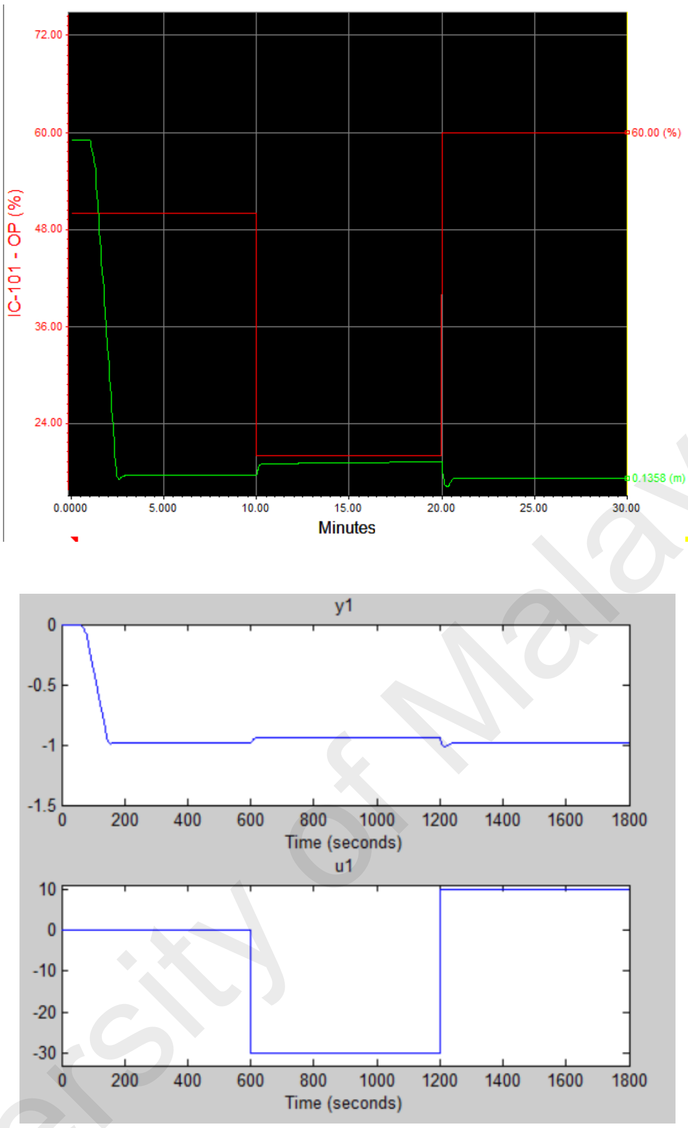


Figure 3.5: Simulation input-output data (control signal and water level) generated from HYSYS

```
A =
           x1
   x1  0.0004187
B =
            u1
   x1  -4.364e-07
C =
         x1
   y1  37.07
D =
       u1
   y1   0
```

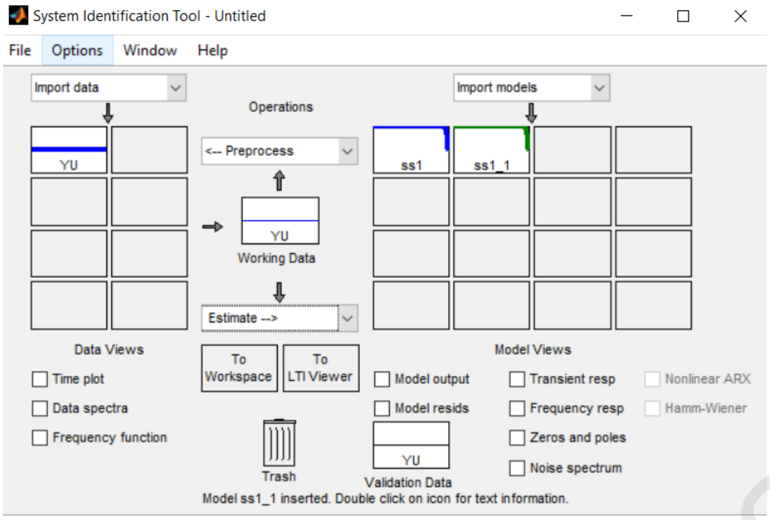


Figure 3.6: System Identification Tool to generate state space model for water level state variable

The state space model is obtained from HYSYS simulation data via MATLAB System Identification Toolbox in Session 3.2.2.

```
A = [0.0004187];
B = [-4.364e-07];
C = [37.07];
D = 0;
[b,a]=ss2tf(A,B,C,D);
G=tf(b,a);
p1 = -1;
K = place(A,B,[p1]);
```

The pole can be calculated using "pole" command. The stability of the system can be checked using the command below.

```
>> pole(G)

ans =

   4.1870e-04

>> isstable(G)

ans =

     0

>> Matrix_contr = ctrb(A,B)

Matrix_contr =

  -4.3640e-07

>> rank(Matrix_contr)

ans =

     1
```

Positive poles value and rank of 0 for stability indicate system is unstable.

On the other hand, rank of 1 for controllability indicates the system is controllable.

3.3. Matlab SIMULINK

A SIMULINK state space model is created for open loop system as a base case, followed by full state feedback control.

The state space representation introduced and state space form is given below.

$$\dot{x} = Ax(t) + Bu(t) \tag{3.18}$$

$$y(t) = Cx(t) + Du(t) \tag{3.19}$$

A controller is built for liquid level and water level system respectively using a pole placement approach. Figure 3.8 is the schematic of a full-state feedback system. Full-states means that all state variables are known by controller all the time. The full state feedback controller is further improved by designing feedforward gain and later added with integral action. Murray (2003) states that adding an integral action to state space feedback controller theoretically is able to achieve zero steady state error. An extra state which is the integral of the output error is to be added. This approach also has the benefit of being robust to variations in the system matrix (A, B, C, D). All these different controllers are analysed in terms of their tracking ability to set point changes. The controller's disturbance rejection is also observed to evaluate each of the system's robustness. An observer is to be designed if is required to calculate state variables that are not accessible from the plant.

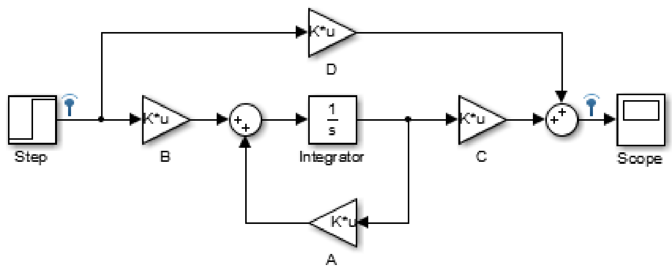


Figure 3.7: Open loop system (without any control)

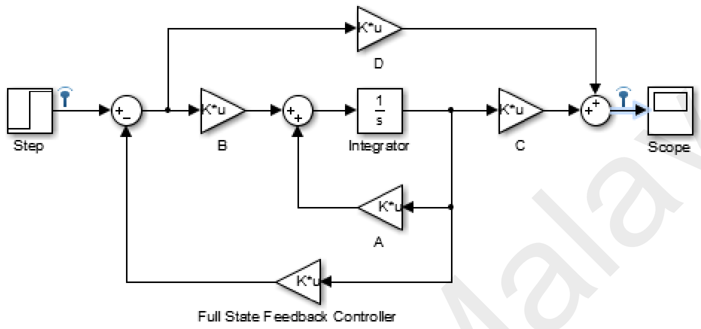


Figure 3.8: Full state feedback control (pole placement method)

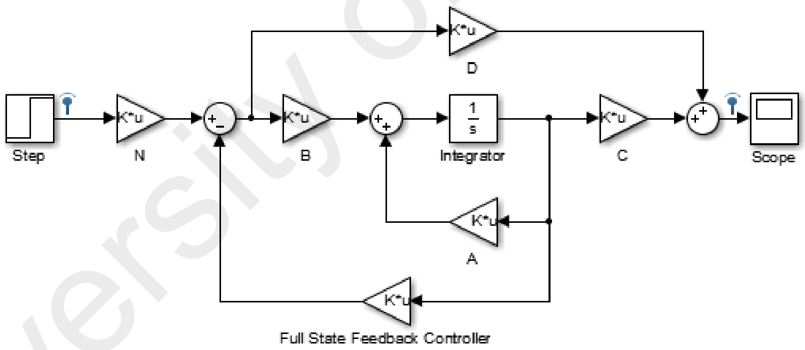


Figure 3.9: State feedback controller with feedforward gain

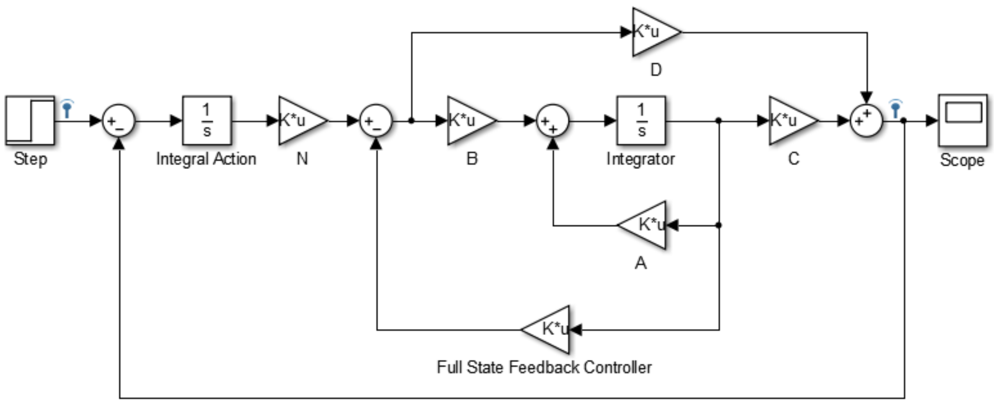


Figure 3.10: State feedback tracking controller

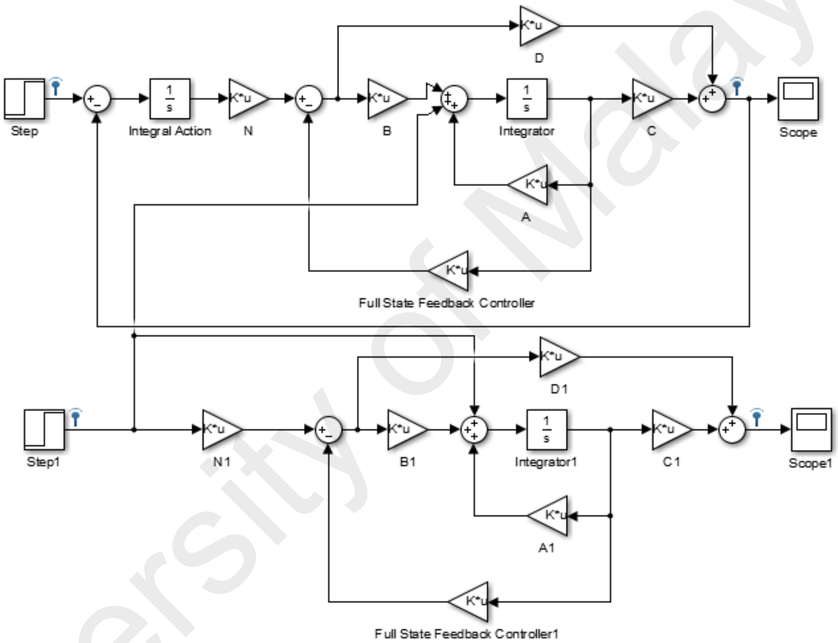


Figure 3.11: Disturbance rejection comparison between state feedback controller with feedforward gain with and without integral action

Chapter 4: Results

4.1. Matlab Simulation Results from Mathematical Modelling Data

4.1.1. Total Liquid (Oil Plus Water) Level State Space Control

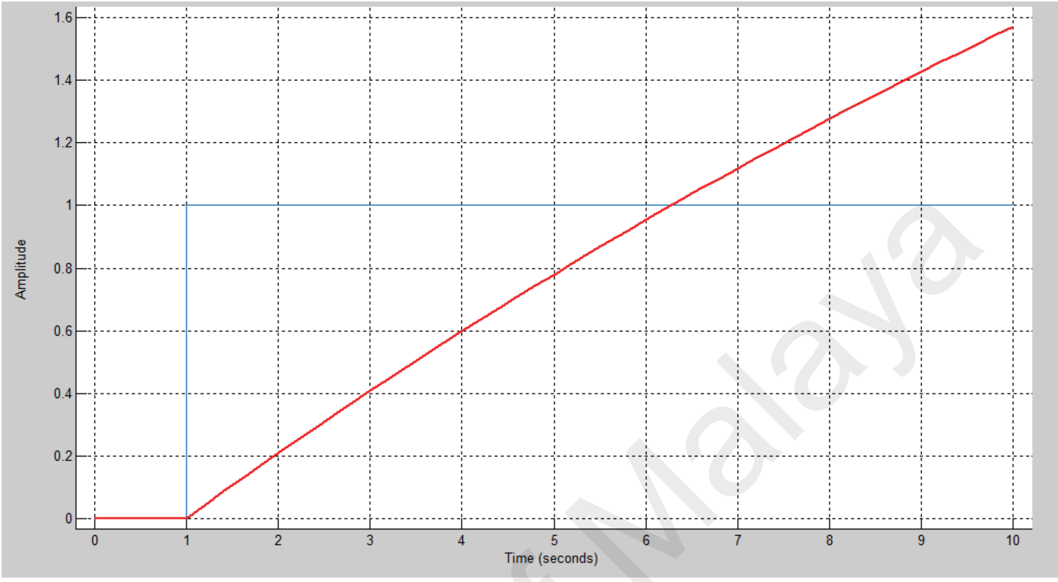


Figure 4.1: Open loop system response to step input in 10s (liquid level control with mathematical modelling data)

Figure 4.1 shows that the open loop of the liquid level response to step input is observed within the time range of 0 to 10 seconds. There is a huge steady state error whereby the system response is going to infinity.

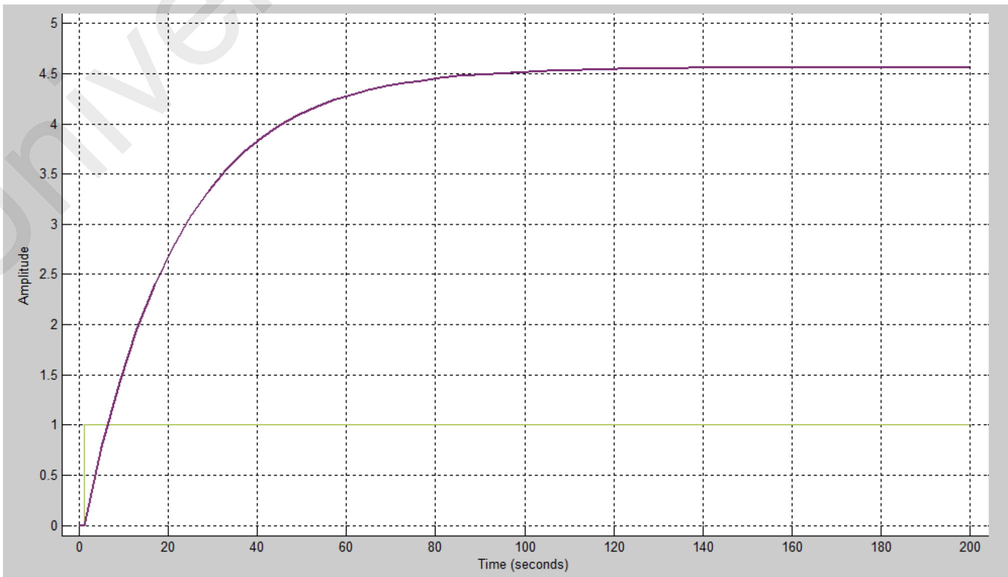


Figure 4.2: Open loop system response to set input in 200s (liquid level control with mathematical modelling data)

In order to track the open loop settling time, the sampling time is increased from 10s to 200s as shown in Figure 4.2. From there, the settling time at round 80s is observed.

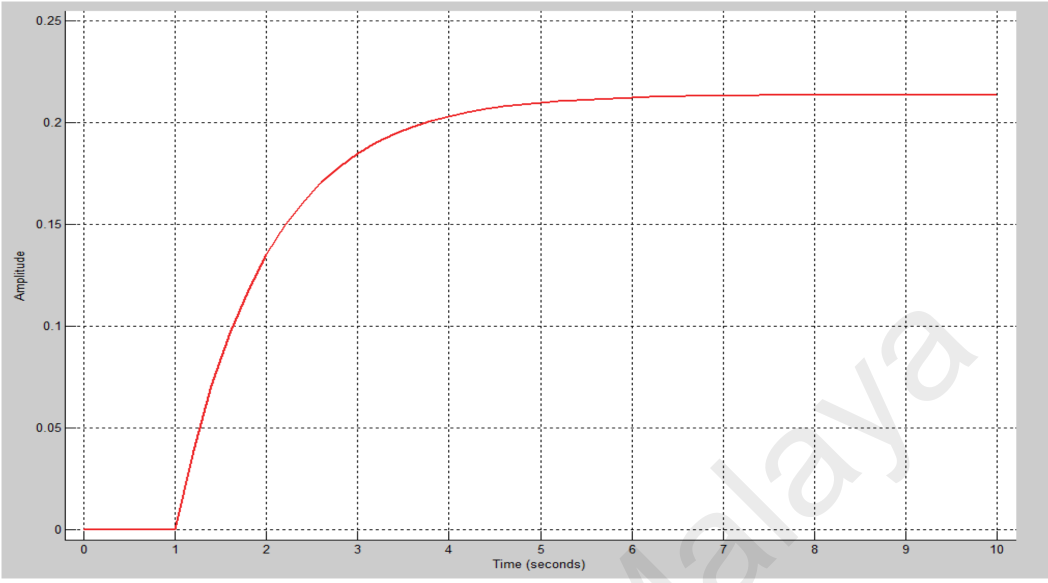


Figure 4.3: Full state feedback controller (liquid level control with mathematical modelling data)

After implemented state feedback as follows. System response is much faster. Rise time 4.11s and settling time 7.31s are much faster as compared to open loop; nonetheless, the steady state error is rather huge.

Feedforward gain is calculated using the formula below to further fine tune the full state feedback controller.

$$N = N_u + KN_x \tag{4.1}$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} O \\ I \end{bmatrix} = \begin{bmatrix} -0.1874 & 0.5 \\ 0.4277 & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4.2}$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} 2.338 \\ 0.8763 \end{bmatrix}$$

$$N = 0.8763 + (1.9063)(2.338)$$

$$N = 5.333$$

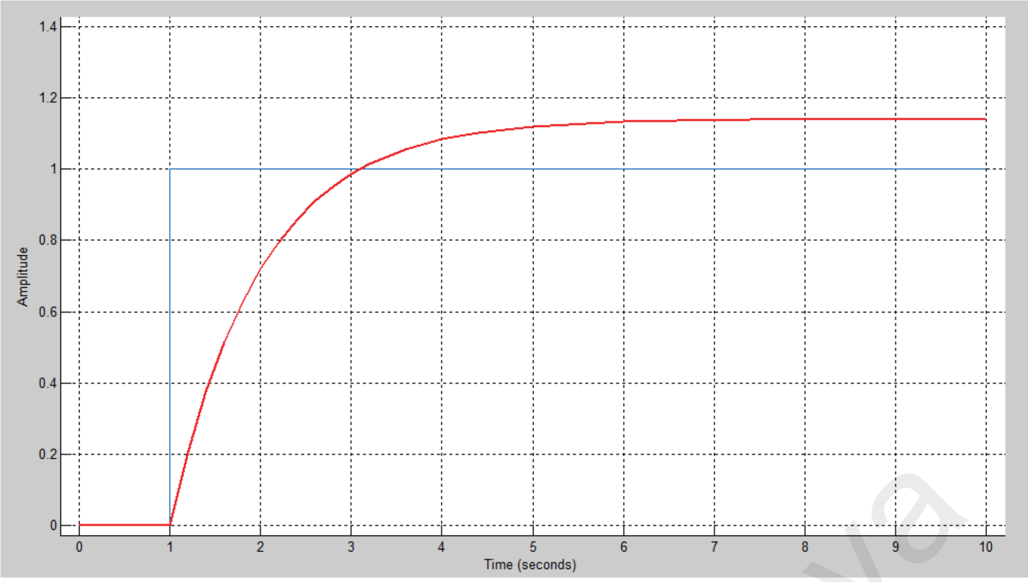


Figure 4.4: State feedback controller with feedforward gain (liquid level control with mathematical modelling data)

New A matrix is generated with the additional of integral action.

$$A^* = \begin{bmatrix} A - BK & BN \\ -C & D \end{bmatrix} \tag{4.3}$$

$$A^* = \begin{bmatrix} -0.1874 - 0.5K & 0.5N \\ -0.4277 & 0 \end{bmatrix}$$

$$Solve, |sI - A^*| = 0 \tag{4.4}$$

$$s^2 - (0.1874 - 0.5K)s + 0.2139N = 0$$

If the desired eigenvalues of the closed loop system are placed at -1, -2, the characteristic equation becomes

$$(s + 1)(s + 2) = s^2 + 3s + 2 = 0$$

Matching the coefficients gives,

$$-0.1874 + 0.5K = 3$$

$$K = 6.38$$

$$0.2139N = 2$$

$$N = 9.35$$

If the desired eigenvalues of the closed loop system are placed at -2, -3, the characteristic equation becomes

$$(s+2)(s+3) = s^2 + 5s + 6 = 0$$

Matching the coefficients gives,

$$-0.1874 + 0.5K = 5$$

$$K = 10.38$$

$$0.2139N = 6$$

$$N = 28.05$$

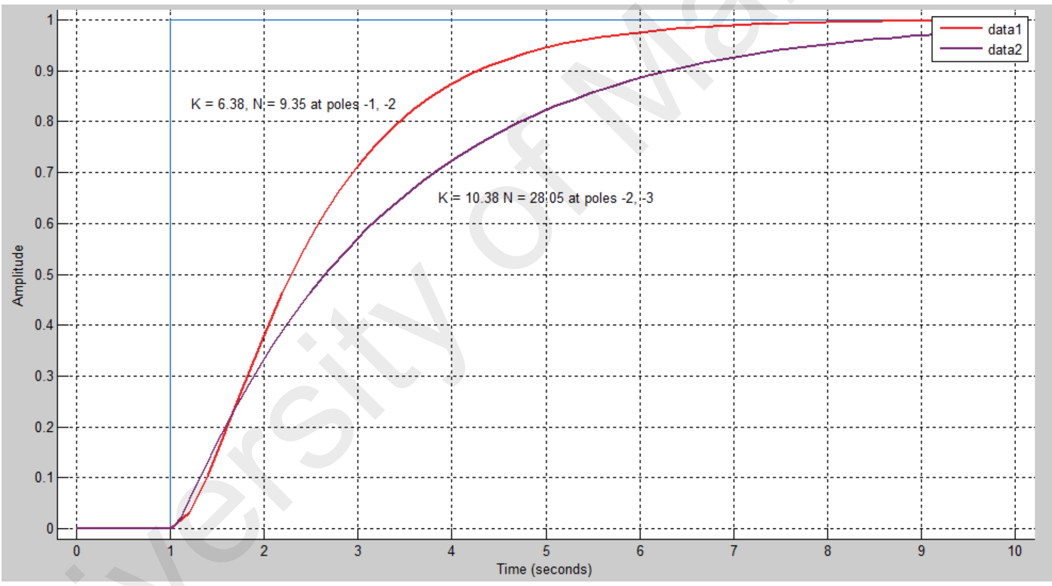


Figure 4.5: State feedback with tracking control/integral action (liquid level control with mathematical modelling data)

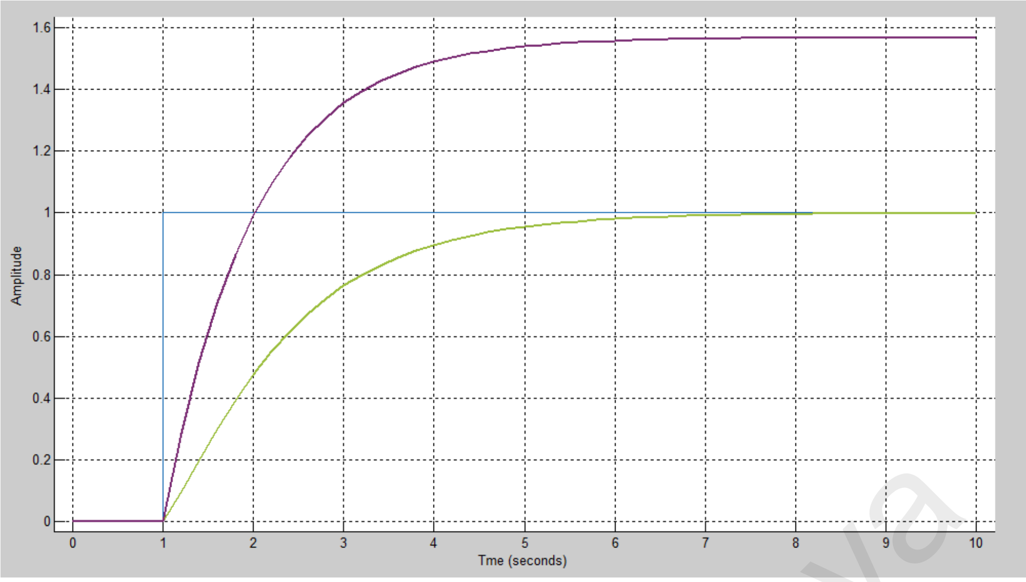


Figure 4.6: Disturbance rejection (liquid level control with mathematical modelling data)

Full state feedback controller with feedforward gain where poles at -1, -2 is having significant steady state error as compared to the system with integral action which has zero steady state error when disturbance is injected (as indicated in Figure 4.6).

4.1.2. Water Phase Level State Space Control

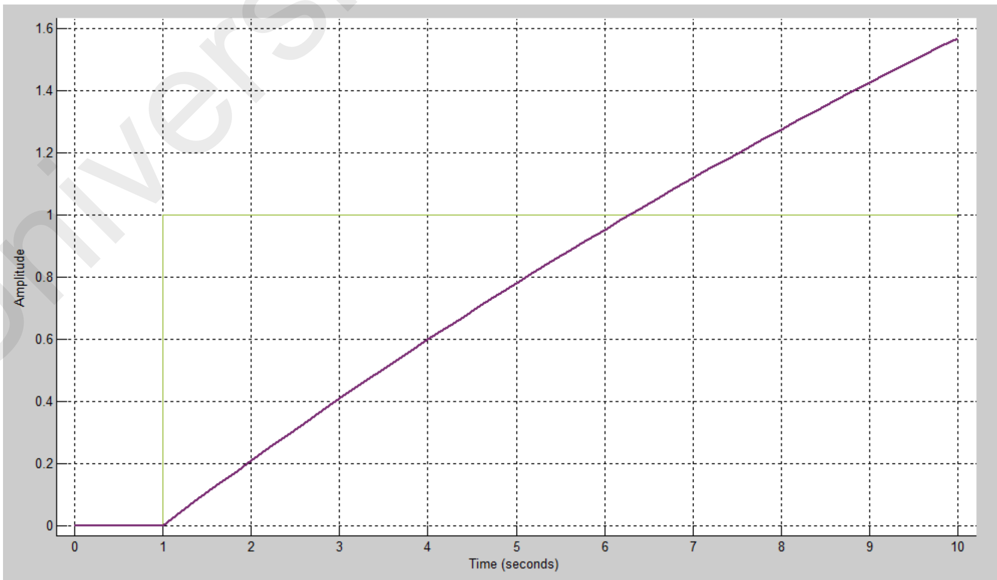


Figure 4.7: Open loop system response to step input in 10s (water level control with mathematical modelling data)

Figure 4.7 illustrates that the open loop of the water level response to step input is observed within the time range of 0 to 10 seconds. It is observed that the steady state error is huge in which the system response is going to infinity.

When sampling time extended to 200s, the open loop system is observed to have rise time 46.9s and settling time at 83.5s which is very slow response and large steady state error.

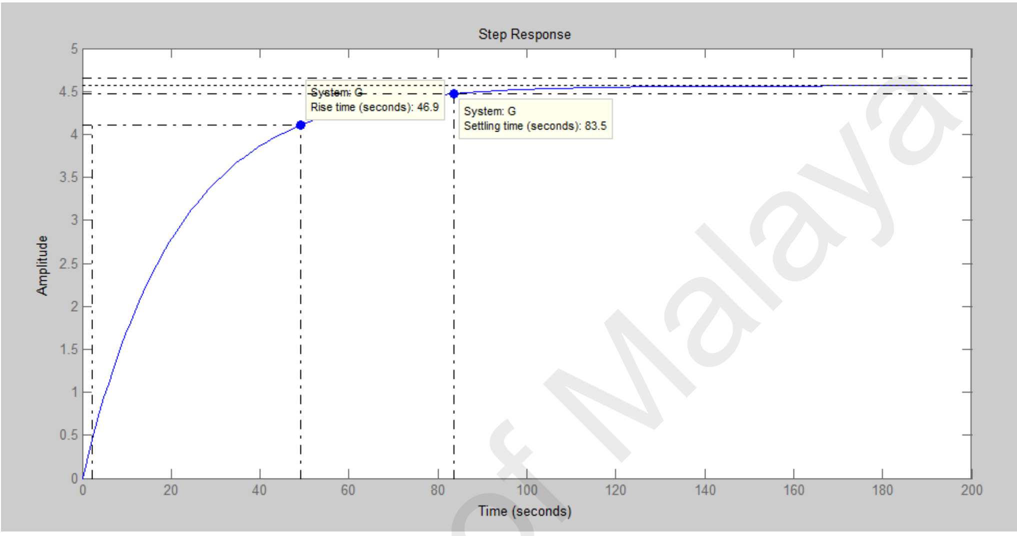


Figure 4.8: Open loop system response to set input in 200s (water level control with mathematical modelling data)

After implemented feedback control as follows. System response is much faster but still with steady state error. Rise time 3s and settling time 5s much faster as compared to before.

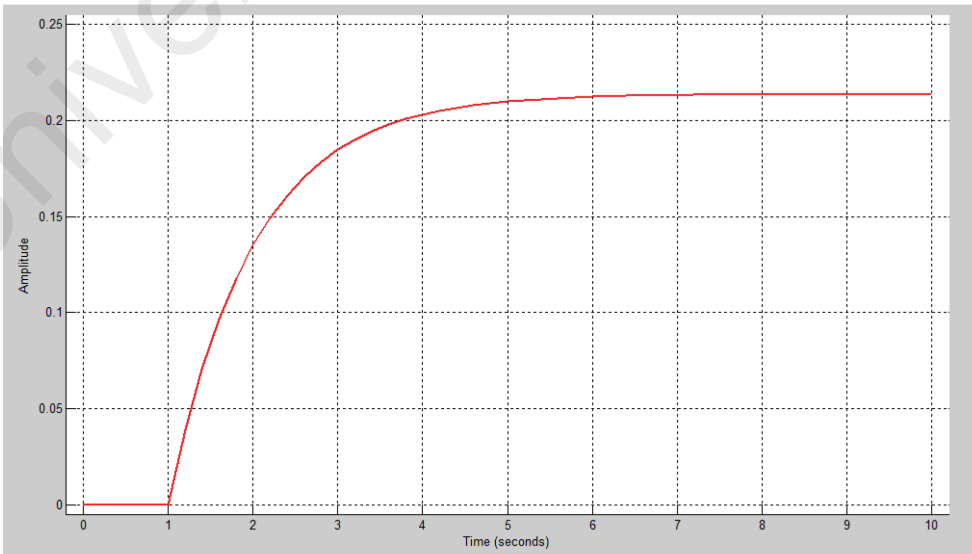


Figure 4.9: Full state feedback controller (water level control with mathematical modelling data)

The system is further improved by implementing feedforward control.

$$N = N_u + KN_x \tag{4.5}$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} O \\ I \end{bmatrix} = \begin{bmatrix} -0.04685 & 0.5 \\ 0.4277 & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4.6}$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} 2.338 \\ 0.219 \end{bmatrix}$$

$$N = 0.219 + (1.9063)(2.338)$$

$$N = 4.676$$

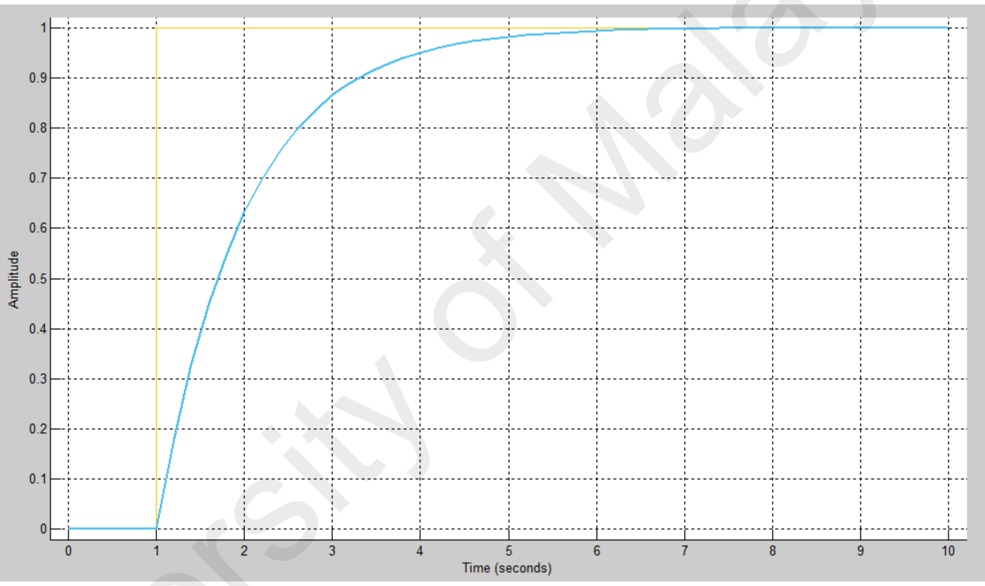


Figure 4.10: State feedback controller with feedforward gain (water level control with mathematical modelling data)

In addition to the state feedback, a weighted integrator is added into the forward path. Note that the state vector is now of dimension (n+1) and an extra poles is required. The state equations have to be changed to reflect the new control structure.

$$A^* = \begin{bmatrix} A - BK & BN \\ -C & D \end{bmatrix} \tag{4.7}$$

$$A^* = \begin{bmatrix} -0.04685 - 0.5K & 0.5N \\ -0.4277 & 0 \end{bmatrix}$$

$$Solve, |sI - A^*| = 0 \tag{4.8}$$

$$s^2 - (0.04685 - 0.5K)s + 0.2139N = 0$$

If the desired eigenvalues of the closed loop system are placed at -1, -2, the characteristic equation becomes

$$(s+1)(s+2) = s^2 + 3s + 2 = 0$$

Matching the coefficients gives,

$$-0.04685 + 0.5K = 3$$

$$K = 6.09$$

$$0.2139N = 2$$

$$N = 9.35$$

If the desired eigenvalues of the closed loop system are placed at -2, -3, the characteristic equation becomes

$$(s+2)(s+3) = s^2 + 5s + 6 = 0$$

Matching the coefficients gives,

$$-0.04685 + 0.5K = 5$$

$$K = 10.09$$

$$0.2139N = 6$$

$$N = 28.05$$

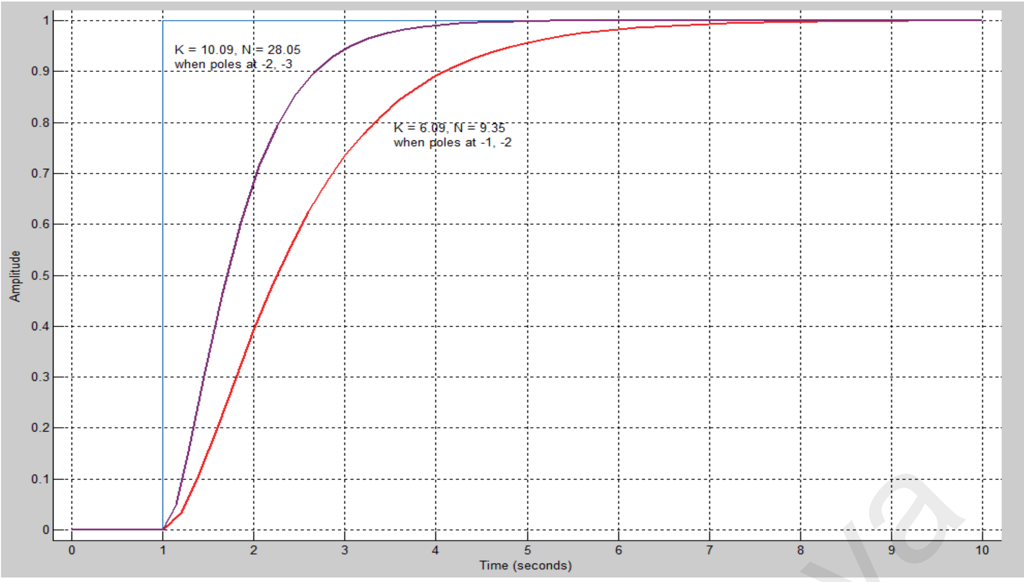


Figure 4.11: State feedback tracking control/integral action (water level control with mathematical modelling data)

In Figure 4.11, it is observed that when the poles placed more to the left, the system seems to respond faster.

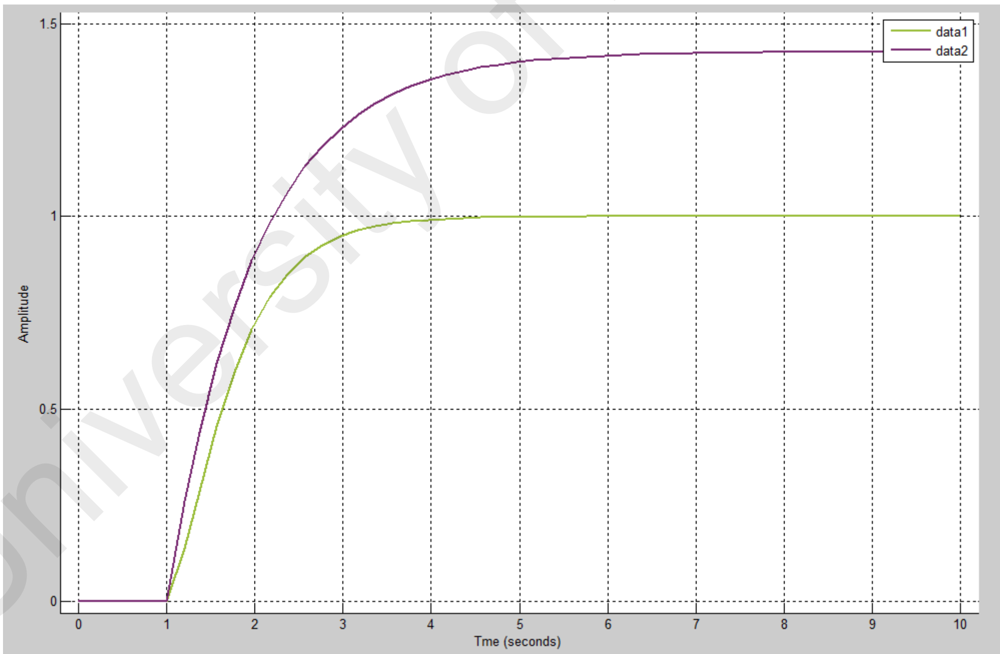


Figure 4.12: Disturbance rejection (water level control with mathematical modelling data)

Sate feedback controller with feedforward gain where poles at -1, -2 is having significant steady state error as compared to the system with integral action which has zero steady state error when disturbance is injected (as indicated in Figure 4.12).

4.2. Matlab Simulation Results from HYSYS Modelling Data

4.2.1. Liquid Level State Space Control

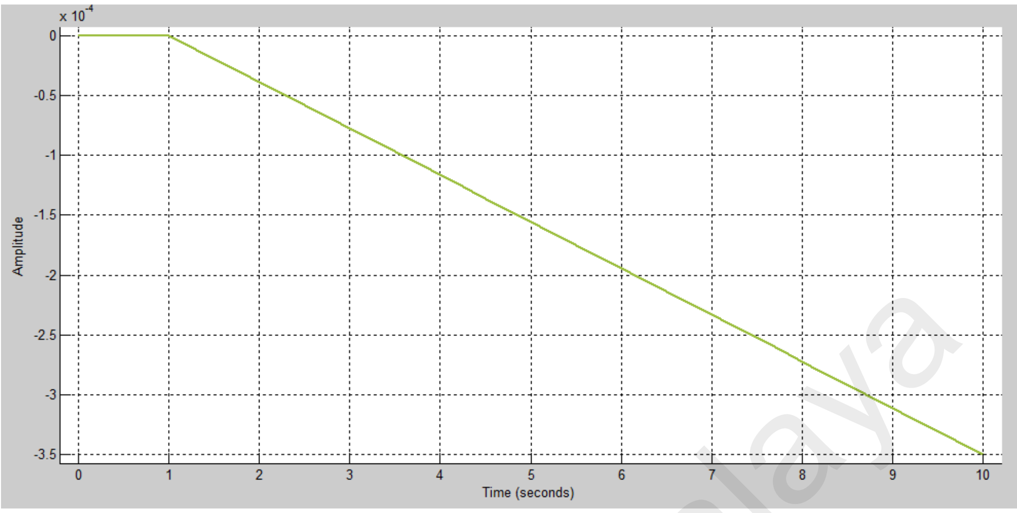


Figure 4.13: Open loop system response to step input (liquid level control with HYSYS modelling data)

In Figure 4.13, open loop system is observed to be unstable which is aligned to the previous result from Matlab command.

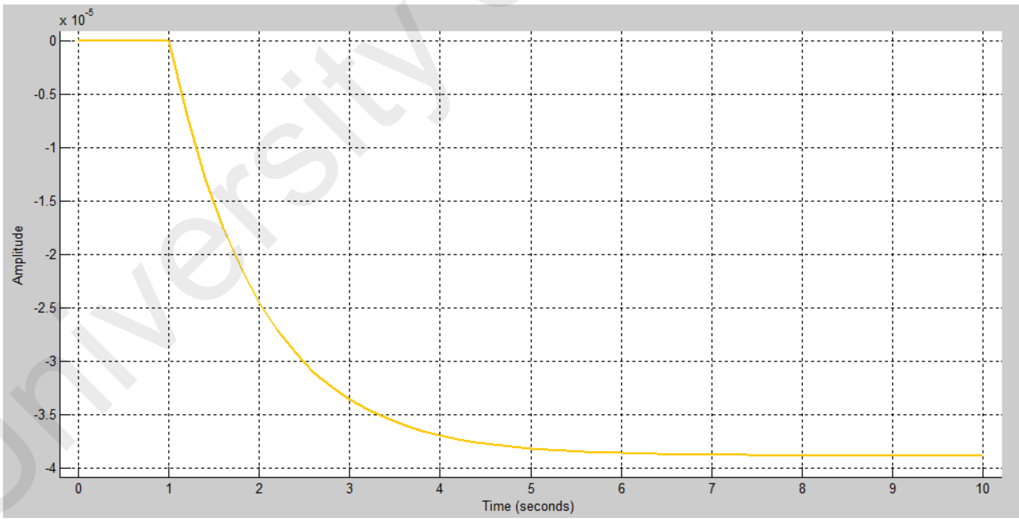


Figure 4.14: Full state feedback controller (liquid level control with HYSYS modelling data)

In Figure 4.14, full state feedback controller shows negative value with large steady state error in response to step input. Thus, there is a need to further fine tune by implementing feedforward controller.

Feedforward gain is calculated using the formula below.

$$N = N_u + KN_x \quad (4.9)$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} O \\ I \end{bmatrix} = \begin{bmatrix} 0.0001191 & -5.07 \times 10^{-6} \\ 7.662 & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (4.10)$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} 0.1305 \\ 3.0659 \end{bmatrix}$$

$$N = 3.0659 + (-1.9726 \times 10^5)(0.1305)$$

$$N = -2.574 \times 10^4$$

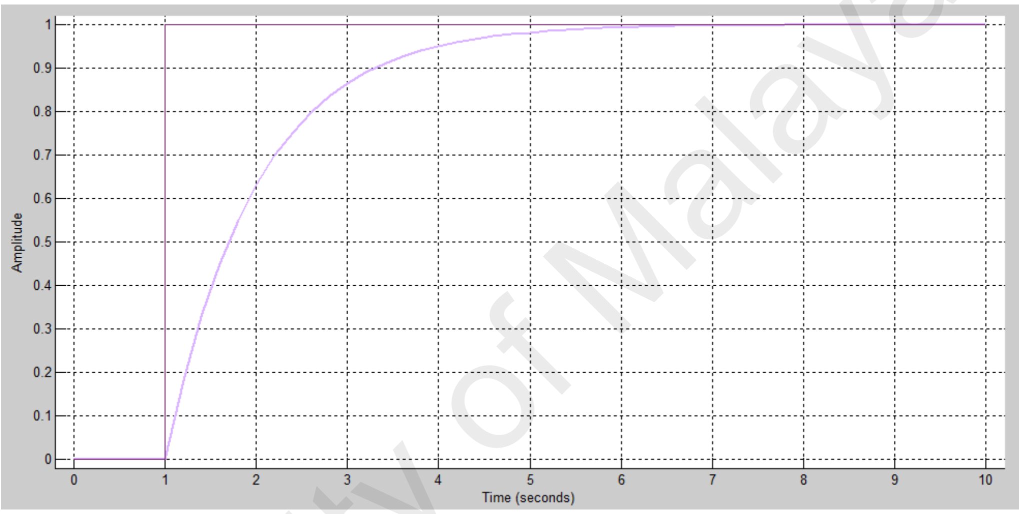


Figure 4.15: State feedback controller with feedforward gain (liquid level control with HYSYS modelling data)

In addition to meeting the settling time requirement, steady state error is also eliminated as shown in Figure 4.15.

In addition to the state feedback, a weighted integrator is added into the forward path. Note that the state vector is now of dimension (n+1) and an extra pole is required. The state equations have to be changed to reflect the new control structure.

$$A^* = \begin{bmatrix} A - BK & BN \\ -C & D \end{bmatrix} \quad (4.11)$$

$$A^* = \begin{bmatrix} 0.0001191 + 5.07 \times 10^{-6}K & -5.07 \times 10^{-6}N \\ -7.662 & 0 \end{bmatrix}$$

$$Solve, |sI - A^*| = 0 \quad (4.12)$$

$$s^2 - (0.0001191 + 5.07 \times 10^{-6}K)s - 3.89 \times 10^{-5}N = 0$$

If the desired eigenvalues of the closed loop system are placed at -1, -2, the characteristic equation becomes

$$(s + 1)(s + 2) = s^2 + 3s + 2 = 0$$

Matching the coefficients gives,

$$-0.000119 - 5.07 \times 10^{-6}K = 3$$

$$K = -5.92 \times 10^5$$

$$-3.89 \times 10^{-5}N = 2$$

$$N = -5.15 \times 10^4$$

If the desired eigenvalues of the closed loop system are placed at -2, -3, the characteristic equation becomes

$$(s + 2)(s + 3) = s^2 + 5s + 6 = 0$$

Matching the coefficients gives,

$$-0.000119 - 5.07 \times 10^{-6}K = 5$$

$$K = -9.86 \times 10^5$$

$$-3.89 \times 10^{-5}N = 6$$

$$N = -1.55 \times 10^5$$

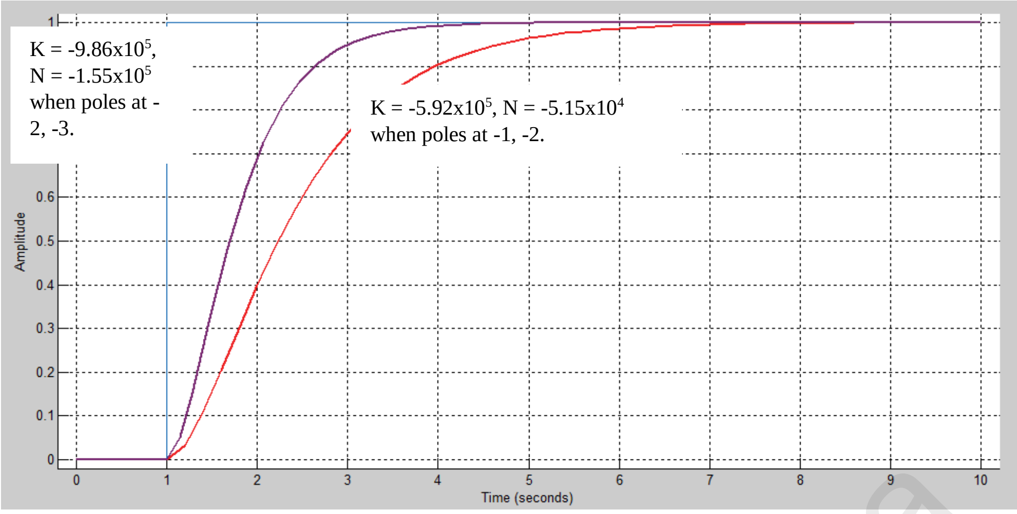


Figure 4.16: State feedback with tracking control/integral action (liquid level control with HYSYS modelling data)

In Figure 4.16, it is observed that when the poles placed more to the left, the system seems to respond faster.

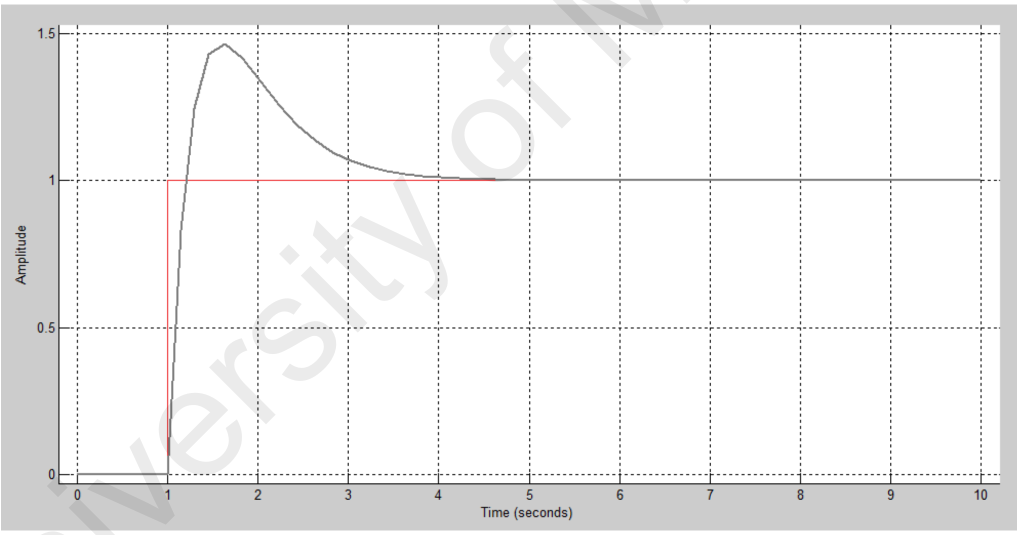


Figure 4.17: Disturbance rejection of system with integral action (liquid level control with HYSYS modelling data)

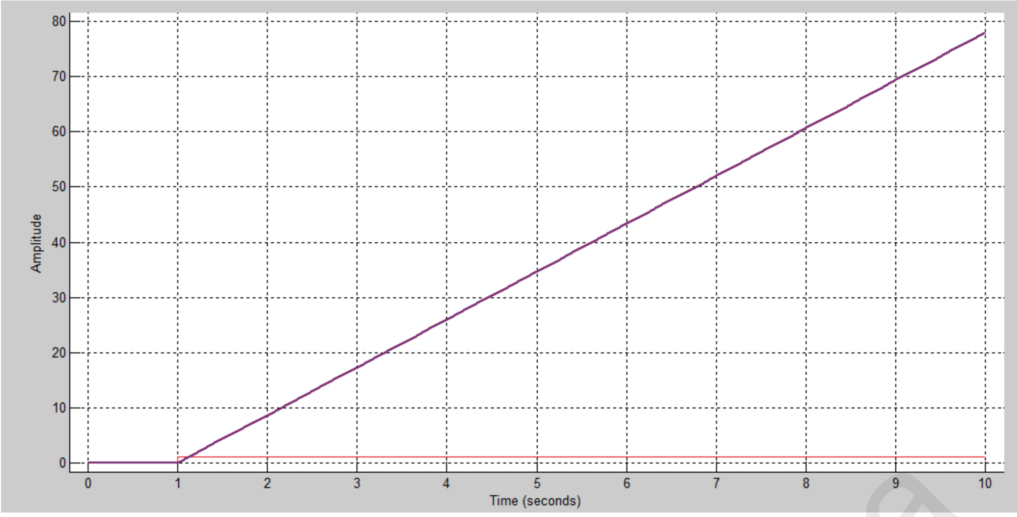


Figure 4.18: Disturbance rejection of system without integral action (liquid level control with HYSYS modelling data)

With reference to Figure 4.17 & 4.18, it is noticed that the system with integral action is more robust in terms of disturbance rejection, whereas the system without integral action is unable tolerate to disturbance and becomes unstable (output goes to infinity as time approaches infinity).

4.2.2. Water Phase Level State Space Control

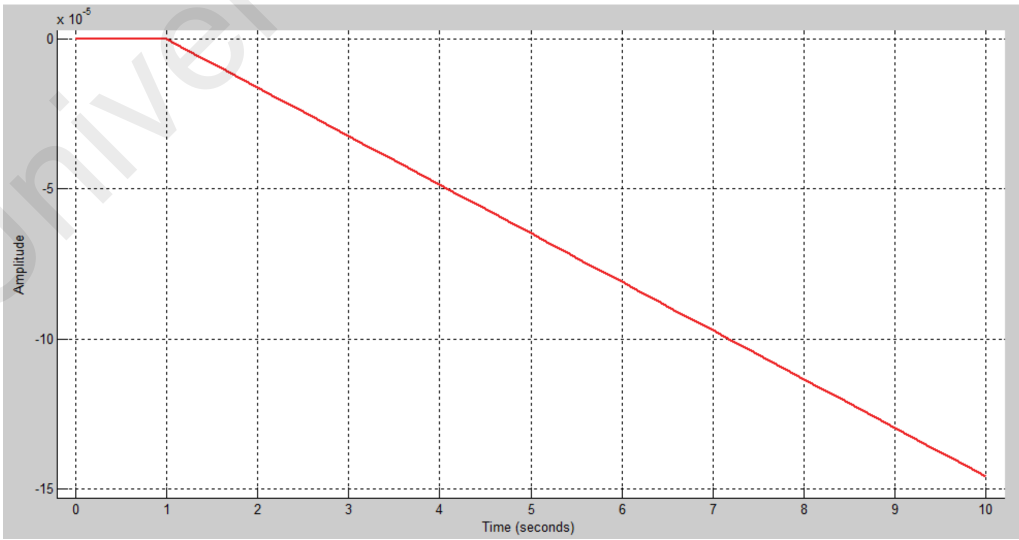


Figure 4.19: Open loop system response to step input (water level control with HYSYS modelling data)

Figure 4.19 shows that the open loop system is unstable which is aligned to the previous result from Matlab command in which the output goes to infinity as time approaches infinity

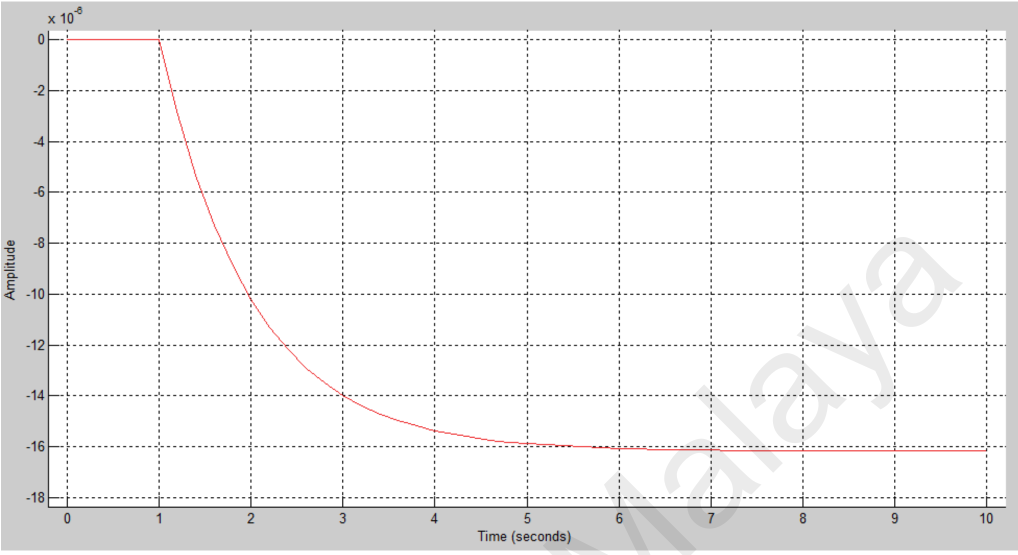


Figure 4.20: Full state feedback controller (water level control with HYSYS modelling data)

In Figure 4.20, full state feedback controller shows negative value with large steady state error in response to step input. Thus, there is a need to further fine tune by implementing feedforward controller.

Feedforward gain is calculated using the formula below.

$$N = N_u + KN_x \tag{4.13}$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} O \\ I \end{bmatrix} = \begin{bmatrix} 0.0004187 & -4.364 \times 10^{-7} \\ 37.07 & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4.14}$$

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} 0.0269 \\ 25.881 \end{bmatrix}$$

$$N = 25.881 + (-2.2924 \times 10^6)(0.1305)$$

$$N = -2.991 \times 10^5$$

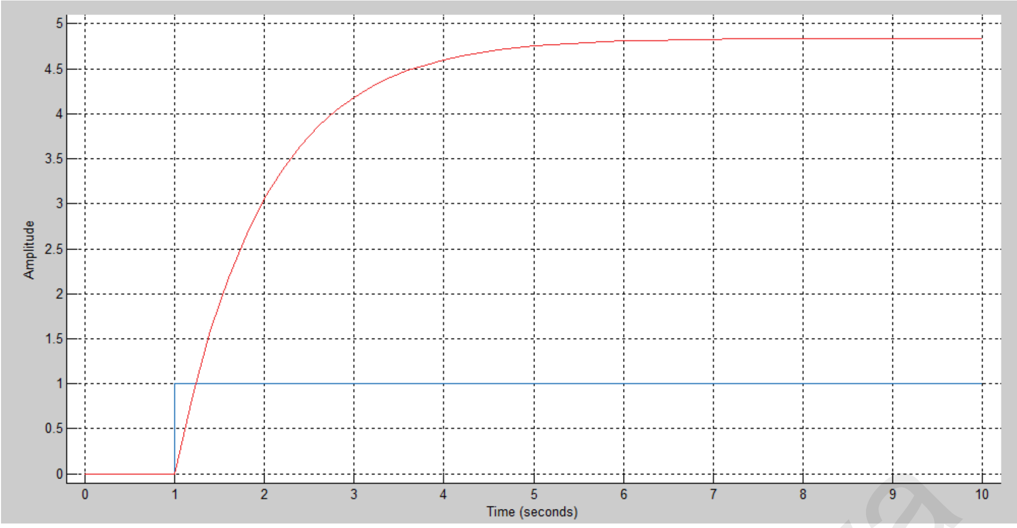


Figure 4.21: State feedback controller with feedforward gain (water level control with HYSYS modelling data)

After added feedforward gain into the state feedback controller, it is observed that the system corrected and able to settle, however, with significant steady state error which needs to be further eliminated.

To eliminate the steady state error, a weighted integrator is added into the forward path. Note that the state vector is now of dimension (n+1) and an extra pole is required. The state equations have to be changed to reflect the new control structure.

$$A^* = \begin{bmatrix} A - BK & BN \\ -C & D \end{bmatrix} \quad (4.15)$$

$$A^* = \begin{bmatrix} 0.0004187 + 4.364 \times 10^{-7}K & -4.364 \times 10^{-7}N \\ -37.07 & 0 \end{bmatrix}$$

$$Solve, |sI - A^*| = 0 \quad (4.16)$$

$$s^2 - (0.0004187 + 4.364 \times 10^{-7}K)s - 1.62 \times 10^{-5}N = 0$$

If the desired eigenvalues of the closed loop system are placed at -1, -2, the characteristic equation becomes

$$(s + 1)(s + 2) = s^2 + 3s + 2 = 0$$

Matching the coefficients gives,

$$-0.0004187 - 4.364 \times 10^{-7}K = 3$$

$$K = -6.88 \times 10^{6}$$

$$-1.62 \times 10^{-5}N = 2$$

$$N = -1.24 \times 10^{5}$$

If the desired eigenvalues of the closed loop system are placed at -2, -3, the characteristic equation becomes

$$(s + 2)(s + 3) = s^2 + 5s + 6 = 0$$

Matching the coefficients gives,

$$-0.0004187 - 4.364 \times 10^{-7}K = 5$$

$$K = -1.15 \times 10^{7}$$

$$-1.62 \times 10^{-5}N = 6$$

$$N = -3.71 \times 10^{5}$$

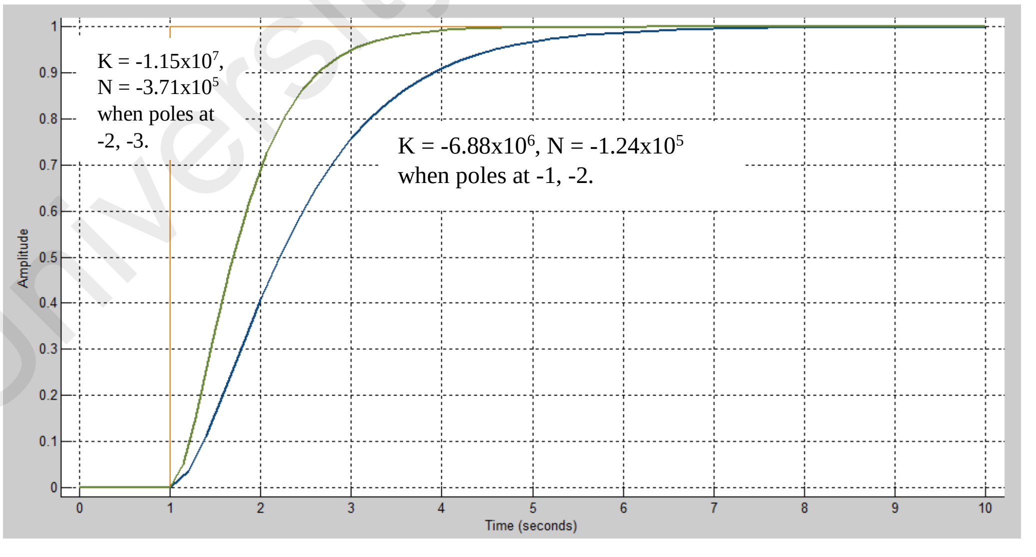


Figure 4.22: State feedback with tracking control/integral action (water level control with HYSYS modelling data)

Figure 4.22 shows that the state feedback with integral action is able to eliminate the steady state error. It is also observed that when the poles placed more to the left, the system seems to respond faster.

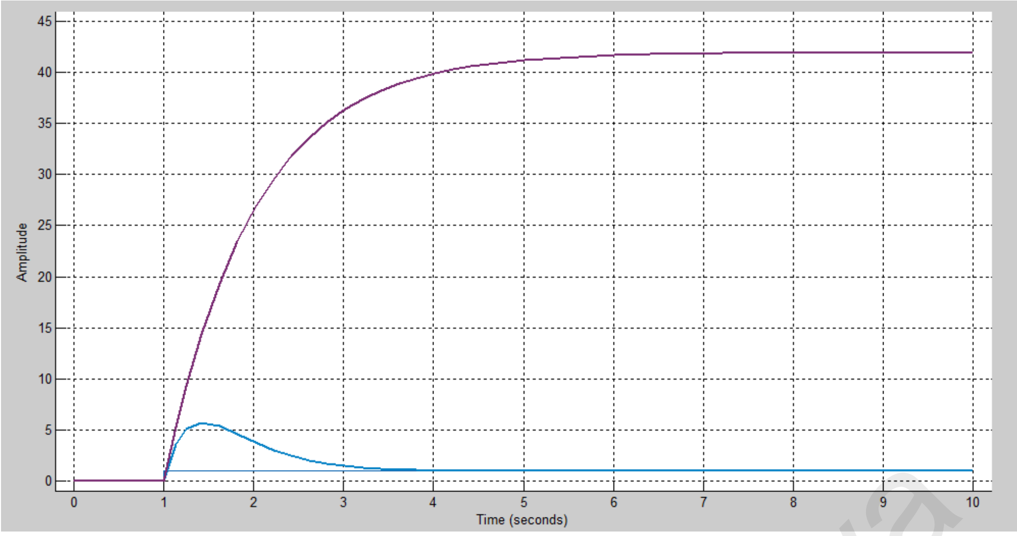


Figure 4.23: Disturbance rejection of system with and without integral action (water level control with HYSYS modelling data)

In terms of disturbance rejection, the state feedback system without integral action is unable to reject disturbance effectively, the disturbance has caused a large overshoot and steady state error up to 42% of the unit step input. Whereas system with integral action, the overshoot corresponding to unit step response is 5% and settled within 3.5s with no steady state error. It is clear that the tracking system is more robust as compared with the few previous controller design.

Chapter 5: Discussion

The main objective of this study is to model and optimize the performance of level control system of an offshore three-phase separator which is a crucial equipment at offshore facilities in oil separation process with constant pressure. An optimal separation process should achieve low oil in water ratio in discharge water, high purity of crude oil (degassing), eliminate liquid carry over to gas, efficient wet gas recovery, maintaining pressure setpoint for export, gas lift or even as fuel for gas turbine generator, and able to dampen disturbances like slugging.

In real plant, PI controller is the most common type of controller being used in the industrial due to its simplicity and effectiveness. Nevertheless, when dealing with unexpected situation such as disturbances, the system robustness and its ability to reject disturbance in a tolerable time frame is also one of the key factors that need to be considered during the controller design.

In this research, state space control (modern control) has been investigated for its suitability in controlling interface level and water level control in three-phase separator. The three-phase separator was modelled using mathematical modelling and HYSYS methods. By using the MATLAB command and open loop system simulation, the mathematical model was found to be stable and controllable even with large steady state error; whereas for HYSYS model, the system was found to be unstable but controllable. This implies that the mathematical model is rather simplified as it merely represents the steady state of the system, unlike HYSYS model which also represents the dynamic state of the system which is more realistic.

A state feedback control system was introduced and analysed, simulation results show that feedback gain is able to stabilize the system but with steady state error. Forward gain was then introduced to eliminate the steady state error. However, forward gain will only work in the case where reference input has a step-wise change only. The design is not considered robust as any changes in the system parameter will cause non-zero error.

Integral control using state feedback was introduced in the forward path of the system to increase robustness of the design. Integral action was added as well as output was fed back to the input of the integrator. With integral action, an extra state had to be added which may increase the complexity in solving the state equations. The simulation results show that state feedback controller with integral action can achieve zero steady state error and also able to dampen disturbance such as waxy crude or sluggish. By placing poles slightly farther to the left, system response and rise time can be further improved.

Chapter 6: Conclusion

In this research, a mathematical steady state and HYSYS dynamic models have been developed and simulated in MATLAB to investigate the performance of state space control using various control methods. After comparing the obtained simulation results, it can be concluded that state space control is able to control the crude oil separation process as desired while rejecting disturbances such as waxy crude or sluggish without causing process upsets. In addition to that, by implementing integral action control, fast response time and zero steady state error can be achieved which means that process fluctuation can be minimized and system response faster in which it would help to improve the overall separation process efficiency.

One of the future work that can be proposed is the implementation of state space control in the real plant to validate its performance against simulation results while taking into account of more variety of disturbances and various operating conditions. Further to that, its performance can be compared to other controller for instance PI controller, IMC controller, MPC controller and etc. to determine the suitability of state space control to implement in offshore facilities in terms of practicability, prospects and costs. Last but not least, in real plant, there are state variables which often cannot be measured, a state observer needs to be designed to estimate them.

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