Design of a Control System for Air Cooler Heat Exchanger

A Case Study of Khartoum Petrochemical Company, Khartoum State, Sudan.

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B.Sc. (Honors) in Chemical Engineering Technology
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Date: 11, September, 2018
Dedication

To my parents, friends, teachers and work fellows, and for their limitless support and encourage, I express my gratitude for the honest feelings and I dedicate to them this work.

Mohamed Obeid Elsayed Elzubair
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Sincerest thanks and praises to my God for his graces upon me, for Islam, health, strength and enabling me doing this work. I would like to thank the staff members of the Department of Chemical Engineering and Chemical Technology of University of Gezira for their appreciatory support.

Finally special thanks to my supervisor Prof. Gurashi Abdullah Gasmelseed for his tireless support and supervision, and Dr. Imad Eldeen Abdelmoniem Mahajoub for the help and advices.
Heat exchangers that are used in reflux condensing have many sizes and types. The air cooler as heat exchanger is adopted due to high volume of overhead product and large capacity of these heat exchangers. The aim of this study is to design a control system to realize high efficiency, accuracy, safety and long time stable running of air cooler performance with less human intervention. Therefore it is necessary to tightly control the feed into the column and level of the reflux drum. The followed method is calculations designing and analyzing the control systems stability. Control systems are designed, the systems stability are analyzed and cross over conditions are identified by Routh, Root locus and Bode methods, and it’s observed that three methods are within very good agreement and it is concluded that any method of the three can be used for stability analysis and tuning. The adjustable parameters are almost equal; the average was calculated and used in stability analysis. Loops are identified and defined as a process of measuring variable and comparing with set point, then manipulating and adjusting output variable. The values of ultimate gain (\(k_u\)) for loop1 (1.3), loop2 (373), loop3 (73.6), loop4 (17.55) and ultimate period (\(P_u\)) for loop1 (2.762s), loop2 (1.452s), loop3 (4.57s), loop4 (0.89s) and it were taken and used to calculate (\(k_c, \tau_i, \tau_d\)) parameters for each loop. Due to small overshoot values; P-controller has chosen as controller type of loops, and values were (P-loop1=1.37, P-loop2=1.58, P-loop3=2.89, P-loop4=6.37, P-loop air=1.52). Bode plot is a complete method for stability analysis and tuning and therefore it is recommended to be applied, furthermore it’s recommended to use digital or SCADA system instead of analog system for more rapid and accurate performance.
تصميم نظام تحكم لمبادل حراري بنظام الهواء

دراسة حالة بشركة الخرطوم للبترول وكيماويات، ولاية الخرطوم، السودان.

محمد عبيد السيد الزبير

ملخص الدراسة

المبادلات الحرارية لها عدة احجام وانواع تختلف باختلاف الاستخدام والعصر، في هذه الوحدة تستخدم المبادلات الحرارية الهواية، نسبة لكمية المنتج العلوي والسعة العالية لهذه المبادلات. الهدف من هذه الدراسة هو تصميم نظام تحكم لتحقيق الكفاءة العالية والدقة والسلامة والاقتصادية المستمرة لأداء المبادات الحرارية الهواية، مع أقل ما يمكن من التدخل البشري. لذلك كان لابد من تحكم محكم لتغذية ومستوى السائل داخل براميل الراجع. الطريقة المتبعة هي التصميم والتحليل لنظم التحكم. تم تصميم نظام التحكم واجراء تحليل الاستقرار وتحديد الذبذبة الحرجة وذلك بطريقة راوث والمخطط الجزري ورسومات بودي وقد استعملت البيانات من هذه الطرق لضبط معاملات المكسب وزمني التكامل والتفاضل. وقد أظهرت هذه الطرق تقاساً جيداً بينها باستثناء بعض القيم الشاذة وعلى أي من هذه الطرق يمكن استعمالها في تحليل استقرارية الأنظمة وضبطها. القيم القابلة للتحديد شبه متساوية لذا اخذ لها المتوسط لتحليل الاستقرارية، عرفت الدوائر كعملية قياس لمتغير ما ومقارنته مع النقطة المرجعية ثم تعديل مخرجات هذه العملية حسب المطلوب. فكان المكسب النهائي للدائرة 1(1.3) ودائرة 2(1.45) ودائرة 3(3.7) ودائرة 4(6.37) ودائرة المبادل=1.52 وهذ هذا وقد اوضحت الدراسة أن طريقة بودي هي طريقة مكتملة لتحليل الاستقرارية لانظمة وضبطها عليه يوصى بتطبيقها، كما يوصى باستخدام نظام رقمي أو سكادا بدلا عن النظام التناظري لداء ادق واعلى كفاءة.
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List of Abbreviations

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<tr>
<td>Gc</td>
<td>Transfer function of controller</td>
</tr>
<tr>
<td>m1,2</td>
<td>Manipulated variable</td>
</tr>
<tr>
<td>H11,12,22,21</td>
<td>Transfer Function</td>
</tr>
<tr>
<td>K11,12,22,2</td>
<td>Transfer Function</td>
</tr>
<tr>
<td>Sp</td>
<td>Set point</td>
</tr>
<tr>
<td>CC</td>
<td>Concentration Controller</td>
</tr>
<tr>
<td>CT</td>
<td>Concentration Transmitter</td>
</tr>
<tr>
<td>TC</td>
<td>Temperature Controller</td>
</tr>
<tr>
<td>TT</td>
<td>Temperature Transmitter</td>
</tr>
<tr>
<td>LC</td>
<td>Level Controller</td>
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<td>LT</td>
<td>level Transmitter</td>
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<td>Gm</td>
<td>Transfer Function of measuring element</td>
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<td>Gp</td>
<td>Transfer Function of process</td>
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<tr>
<td>num</td>
<td>The numerator of transfer function</td>
</tr>
<tr>
<td>den</td>
<td>The denominator of transfer function</td>
</tr>
<tr>
<td>tf</td>
<td>computes the transfer function</td>
</tr>
<tr>
<td>Sys</td>
<td>Calculate and plot in SISO model sys.</td>
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<tr>
<td>Kc</td>
<td>process gain</td>
</tr>
<tr>
<td>Ku</td>
<td>ultimate gain</td>
</tr>
<tr>
<td>Ti</td>
<td>integral time constant</td>
</tr>
<tr>
<td>Td</td>
<td>Derivative time constant</td>
</tr>
<tr>
<td>P</td>
<td>Proportional Response</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral Response</td>
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<td>PID</td>
<td>Proportional Integral Derivative Response</td>
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1.1 Background

Propylene is one of the main building blocks for petrochemicals and for clean fuel alkylate blends. It is used in the production of a wide variety of petrochemical products such as polypropylene, acrylonitrile, cumene, oxo-alcohols, propylene oxide, acrylic acid, isopropyl alcohol, and polygas chemicals. Polypropylene accounts for about half of the world propylene consumption, which consequently drives the demand. Other uses of propylene within a refinery include alkylation, catalytic polymerization, and dimerization for the production of high-octane gasoline blends. In general, propylene is supplied in three separate quality grades: refinery (70%), chemical (92 to 96%), and polymer (99.6%).

The two major commercial sources of propylene are ethylene steam cracker plants and refinery fluid catalytic cracking (FCC).

Current global production of propylene stands at about 54 million metric tons per year (tpy) and is valued roughly at $17 billion. Propylene demand is expected to grow fast and to nearly double in the next 10 yr, reaching more than 91 million tons by 2010 at a growth rate of 4.7%\textperyear. Because world consumption is forecast to grow faster than production capacity, propylene has been termed as “olefin of the future.” This increase is driven by the demand for derivatives, especially polypropylene. (Abdullah M. A., 2007).

1.2 Background of Project

The purpose of the project is to reasonably utilize propylene of Khartoum Refinery gas to produce value added polypropylene to meet requirement of Sudan local market demands. The united unit is composed of 80000t/a gas separation unit, 18000t/a polypropylene unit. Gas fractionation unit supplies qualified propylene raw material to PP unit, the flow scheme adopts 4 towers gas fractionation process. first remove C4+componenets, and then remove ethane, ethylene, finally separate propane and propylene (Khartoum Petrochemical Company, 2007).
1.3 Control System of Unit

There are a number of basic factors that have direct influence on the control of an operating process system. In a manual control system, these factors are normally performed by a human operator. Automatic systems achieve the same basic functions but through the manipulation of self-regulating controls. As a rule, automatic control operations are much more complex and difficult to achieve than those of a manual system control.

The basic functions of system control include measurement, comparison, computation, and correction. Measurement is essentially an estimate or appraisal of the process being controlled by the system. Comparison is an examination of the likeness of measured values and desired values. Computation is a calculated judgment that indicates how much the measured value and desired operating value differs. Correction is the adjustments which are made in order to alter operating values to a desired level. These functions must all be achieved by an automatic system during the normal course of its operation (Patrick and Fardo, 2009).

The technical process of gas distillation unit is rather complicated, therefore the DCS is used to supervise, control, operate and manage the production, to enhance product quality and process management level.

DCS is abbreviation of Total Distributed Microprocessor Control System.

It is composed by 5 following sections:
1. Input/output process module used in collecting data and supervising input and output.
2. Process control module used in controlling process (successively or by batch).
3. Human-machine interface featured with management function.
4. Communication network connected with all the modules and equipped a hi-speed communication cable.

PCs and their interfaces (Khartoum Petrochemical Company, 2002).
1.4 Statement of the Problem:
Pressure adjusting of reflux vessels by air coolers is done manually, so the intention is to develop a control system that join reflux vessel conditions with air cooler blowers to reduce human errors.

1.5 Scope of Research:
Research covers the following parts:
1. Fractionation theories and methods.
2. Control of columns conditions within process.
3. Design of control system of reflux ratio cooling and condensing.
4. Using different methods and check the stability of the system.
5. Comparing these methods and choose the one that gives the best performance.

1.6 Objectives of Research:
The objectives of this research are to:
1. Develop a controller to reduce human errors during pressure adjusting of reflux vessels.
2. Make tuning and simulation of the control systems.
Chapter Two
Literature Review

2.1 Liquefied Petroleum Gas (LPG):
It is a mixture of hydrocarbon gases, primary propane and butane. The exact composition of LPG varies according to its source, processing principles and depends on the season. LPG is odorless, colorless and non-toxic. To reduce the danger of an explosion from undetected leaks, commercial LPG usually contains an odorizing agent, such as ethanethiol, which gives it a distinctive pungent odor. LPG has a higher calorific value (94 MJ/m³ equivalents to 26.1 kWh) than natural gas (38 MJ/m³ equivalents to 10.6 kWh).

Table 2.1- Properties of LPG (KLM Technology Group, 2018).

<table>
<thead>
<tr>
<th>Name of the property</th>
<th>Value for LPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezing point</td>
<td>-187°C</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.588</td>
</tr>
<tr>
<td>Vapor pressure at 38°C</td>
<td>1212 kPa</td>
</tr>
<tr>
<td>Heat content</td>
<td>50221 kJ/kg</td>
</tr>
</tbody>
</table>

2.2 Process:
LPG feed before entering [depropanizer] it passes by integrating heat exchanger E101 (with bottom product) for preheating. The feed enters T101 by 27th tray. C2/C3 leave by overhead then the mix condensed by air cooler heat exchangers E103, and collected in reflux drum. Uncondensed gases (C2) leave the drum to fuel system. A part of the condensed overhead product is sent back to the column as reflux while the remaining part is sent to T102 [deethanizer]. The bottom product of T101 cooled in the heat integration heat exchanger E101 and then condensed in the next heat exchanger for leaving the unit. C2/C3 mixture enters T102; the overhead product is mainly C2 condensed in107 then leaves to fuel system. Bottom product consists of C3/C3” sent to T103 [propylene tower], which is consists of two columns due to design considerations, the top product of T103 enters T104 from first tray, and bottom product of T104 sent back to T103 and the
bottom product (pure propane) leaves column to E110 then leaves the unit, and so on, top product of T104 (pure propylene) condensed in E111 then collected in reflux drum 104. A part of condensed product sent back to overhead and the remained is further cooled in E112 then sent for storage tanks (Khartoum Petrochemical Company, 2002).

Figure 2.1 Distillation process diagram (Source: Khartoum Petrochemical DCS Display, 2018)

2.3 Fractionation column:
Distillation may be carried out in plate columns in which each plate constitutes a single stage, or in packed columns where mass transfer is between a vapor and liquid in continuous countercurrent flow.

The number of theoretical stages required to effect a required separation, and the corresponding rates for the liquid and vapor phases, may be determined by many procedures.
The following factors should be considered:
(a) The type of plate or tray.
(b) The vapour velocity, which is the major factor in determining the diameter of the column.
(c) The plate spacing, which is the major factor fixing the height of the column when the number of stages is known.

Types of trays:
The main requirement of a tray is that it should provide intimate mixing between the liquid and vapour streams, that it should be suitable for handling the desired rates of vapour and liquid without excessive entrainment or flooding, that it should be stable in operation, and that it should be reasonably easy to erect and maintain. In many cases, particularly with vacuum distillation, it is essential that the drop in pressure over the tray should be a minimum.
The bubble-cap tray. This is the most widely used tray because of its range of operation, although it is being superseded by newer types, such as the valve tray discussed later.

![Figure 2.2 bubble cap tray](Source: Coulson and Richardson’s, 2002)

Sieve or perforated trays. These are much simpler in construction, with small holes in the tray. The liquid flows across the tray and down the segmental downcomer.
Valve trays. These may be regarded as a cross between a bubble-cap and a sieve tray. The construction is similar to that of cap types, although there are no risers and no slots. It may be noted that with most types of valve tray the opening may be varied by the vapor flow, so that the trays can operate over a wide range of flow rates. Because of their flexibility and price, valve trays are tending to replace bubble-cap trays (Coulson and Richardson’s, 2002).

2.4 Heat exchangers:

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact. In heat exchangers, there are
usually no external heat and work interactions. Typical applications involve heating or cooling of a fluid stream of concern and evaporation or condensation of single- or multicomponent fluid streams. In other applications, the objective may be to recover or reject heat, or sterilize, pasteurize, fractionate, distill, concentrate, crystallize, or control a process fluid. In a few heat exchangers, the fluids exchanging heat are in direct contact. In most heat exchangers, heat transfer between fluids takes place through a separating wall or into and out of a wall in a transient manner. In many heat exchangers, the fluids are separated by a heat transfer surface, and ideally they do not mix or leak.

Such exchangers are referred to as direct transfer type, or simply recuperators. In contrast, exchangers in which there is intermittent heat exchange between the hot and cold fluids—via thermal energy storage and release through the exchanger surface or matrix—are referred to as indirect transfer type, or simply regenerators. Such exchangers usually have fluid leakage from one fluid stream to the other, due to pressure differences and matrix rotation/valve switching. Common examples of heat exchangers are shell-and-tube exchangers, automobile radiators, condensers, evaporators, air preheaters, and cooling towers (Shah and Sekulic, 2003). Air cooled heat exchangers are used to transfer heat from a process fluid to ambient air. The process fluid is contained within heat conducting tubes. Atmospheric air, which serves as the coolant, is caused to flow perpendicularly across the tubes in order to remove heat. In a typical air cooled heat exchanger, the ambient air is either forced or induced by a fan or fans to flow vertically across a horizontal section of tubes. For condensing applications, the bundle may be sloped or vertical. Similarly, for relatively small air cooled heat exchanger, the air flow may be horizontal across vertical tube bundles. In order to improve the heat transfer characteristic of air cooled exchanger, the tubes are provided with external fins. These fins can result in a substantial increase in heat transfer surface. Parameters such as bundle length, width and number of tubes rows vary with the particular application as well as the particular finned tube design (Serth, 2007).
2.5 Reflux Drums:

Distillation and fraction processes use reflux drums. Reflux drums collect the condensed overhead product from a column. Uncondensed gases collect in the upper part of the drum. Some of liquids return to the column. This liquid is called reflux. The reminder flows on to other plants for treating storage and sales. (Saudi Aramco, 2002).
2.6 Process control:

Control systems are tightly interwined in our daily lives, so much that we take them for granted. They may be as low-tech and unglamorous as our flush toilet. Or they may be as high-tech as electronic injection in our cars. In fact, there are more than a handful of computer control systems in a typical car that we now drive. Everything from the engine to transmission, shock absorber, brakes, pollutant emission, temperature and so forth, there is an embedded microprocessor controller keeping an eye out for us. The more gadgetry, the more tiny controllers pulling the trick behind our backs. At the lower end of consumer electronic devices, we can bet on finding at least one embedded microcontroller.

In the processing industry, controllers play a crucial role in keeping our plants running—virtually everything from simply filling up a storage tank to complex separation processes, and to chemical reactors.

What are some of the issues when we design a control system? In the first place, we need to identify the role of various variables. We need to determine what we need to control, what we need to manipulate, what are the sources of disturbances, and so forth. We then need to state our design objective and specifications. It may make a difference whether we focus on the servo or the regulator problem, and we certainly want to make clear, quantitatively, the desired response of the system. To achieve these goals, we have to select the proper control strategy and controller. To implement the strategy, we also need to select the proper sensors, transmitters, and actuators. After all is done, we have to know how to tune the controller. Sounds like we are working with a musical instrument, but that's the jargon. The design procedures depend heavily on the dynamic model of the process to be controlled. In more advanced model-based control systems, the action taken by the controller actually depends on the model. Under circumstances where we do not have a precise model, we perform our analysis with approximate models. This is the basis of a field called "system identification and parameter estimation." Physical insight that we may acquire in the act of model building is invaluable in problem solving (Chau, 2001). For further classification of the term into more workable divisions. Control is first classified as being either manual or automatic. This division generally refers to the amount of human effort needed to achieve a common function. Manual control is
voluntarily initiated within the system with very little human effort. The terms open-loop and forward-feed are frequently used to describe manual control systems. Valve adjustments and switching functions are examples of manual control operations. In general, this type of control is achieved by some degree of physical effort on the part of a human operator. Automatic control, by comparison, applies to those things that are achieved, during normal operation, without human intervention. This type of control is used where continuous attention to system operation would be demanded for a long period without interruptions. Automatic control does not, however, necessarily duplicate the type of control achieved by a human operator. Equipment that employs automatic control is limited to only those things that can be forecast by the input data. Terms such as closed-loop control and feedback are commonly used to describe automatic control functions (Chau, 2001).

**2.6.1 Open-loop Control:**

Open-loop control is relatively easy to achieve because it does not employ any automatic equipment to compare the actual output with the desired output. In manufacturing, open-loop operations are achieved by adjustment of the system to some predetermined setting by a human operator. The system then responds to this setting without any modification. Any changes made in operation are based entirely on some outside human judgment to correct the desired output. The open-loop system in Figure 2-1 is composed of a process energy source, a transmission path, a controller, and an actuator or final control element. The process energy source represents input variables such as time, temperature, speed, pressure, flow, displacement, acceleration, and force. The transmission path is responsible for transferring input energy to the remainder of the system. The controller provides intelligence for the system and governs the action of the actuator. The manual setpoint adjustment attached to the controller is used to alter the operating range of the controller. The actuator implements the response of the controller to the final controller element. The final control element can be a motor, pneumatic cylinder, solenoid, or hydraulic valve. The final control element is responsible for altering the process energy passing
through the system. The output is considered to be the controlled process. Examples of controlled processes are water temperature, the pH of a chemical solution, the viscosity of crude oil, the temperature of molten aluminum in a furnace, or the path of a cutting tool on a milling machine.

A period of time is required before any corrective action takes place. If the amount of correction is too great or not enough, the process will need to be repeated. In manual systems of this type, control involves repeated steps of measurement, comparison, computing, and correction. This means that manual control usually demands continuous supervision by the operator, which is a decided disadvantage of this type of system. The primary advantage of open-loop or manual control is simplicity of operation and low-cost installation. The intended accuracy of the process being controlled determines its suitability for manual control. In a strict sense, the operator of a manual control system forms the feedback path from output to input that closes the loop of the control system.

### 2.6.2 Closed-loop Control:

*Closed-loop* refers to a type of system that is self-regulating. In this type of system, the actual output is measured and compared with a predetermined output setting. A feedback signal generated by the output sensing component is used to regulate the control element so that the output conforms to the desired value. The term *feedback* refers to the direction in which the measured output signal is returned to the control element. In a sense, the
output of this type of system serves as the input signal source for the feedback control element.

Closed-loop control is so named because of the return path created by the feedback loop from the output to input.

A brief explanation of some common terms associated with process control is presented here as a general review.

**Process**—Activities performed on raw materials or work pieces to convert them into a finished product are called processes. A process could also be described as an operation utilized to achieve an industrial manufacturing function, such as pressure, temperature, flow, liquid level, mechanical motion, numbers, weight, specific gravity, viscosity, and numerous analytical values.

**Controlled Variable**—Controlled variables are the basic process values being manipulated by a system. These values may vary with respect to time, as a function of other system variables, or both.

**Controllers**—A controller is a hardware piece of equipment that employs pneumatic, electronic, and/or mechanical energy to perform a system control operation. These units are designed to maintain a process variable at a predetermined value by comparing its existing value to that of a desired system value.

**Set point**—A set point is a prescribed or desired value to which the controlled variable of a process system is manually adjusted. It is indicated on the horizontal set point indicator.
Sensor—A sensor is a piece of equipment that is used to measure system variables. Sensors are normally transducers that change energy of one form into something different. Sensors serve as the signal source in automatic control systems.

Control Element—A control element is a part of the process control system that exerts direct influence on the controlled variable to bring it to the set point position. This element accepts output from the controller and performs some type of operation on the process. The term final control element is used interchangeably with control element.

2.6.3 Modes of Control:

The operational response of a controller is often described as its mode of control. Several different types of control are available. In some cases, only a single mode of control is needed to accomplish an operation. This is described as a pure control operation. On-off, proportional, integral, and derivative are examples of pure control.

More sophisticated control is achieved by combining two or more pure modes of operation. This is described as a composite mode. Proportional plus integral, proportional plus derivative, and proportional plus integral plus derivative are examples of composite control modes.

2.6.3.1 On-off Operation:

An on-off or two-state controller is the simplest of all process control operations. The actuator or final control element driven by the output of the controller is automatically switched on or off. It does not have any intermediate level of operation. Control of this type is popular and inexpensive to accomplish.

2.6.3.2 Proportional Control:

In on-off control, the final control element was either on or off. If the control element were a valve, it would have been fully open or closed. There is no intermediate adjustment of the valve. In proportional control, the final control element can be adjusted to any value between fully open and fully closed.

Its value is determined by a ratio of the setpoint input and the actual process value of the system. In a valve-controlled system, operation is arranged so that the valve is normally adjusted to some percentage of its operating range. Proportional control is defined mathematically as
\[ \text{Vout} = K_p \text{Ve} \]

where

- \( \text{Vout} \) = controller output
- \( K_p \) = proportional controller gain
- \( \text{Ve} \) = error signal, or \( \text{Vsp} - \text{Vpv} \)

As a rule, proportional control works well in systems where the process changes are quite small and slow.

A disadvantage of proportional control is that it does not respond well to long-term or steady-state changes in the process being controlled.

A change or disturbance will not let the process return exactly to its pre-disturbance value. This means that the process will have a difference in its new value. This is called an \textit{offset}. It represents a new process value that is slightly less than the setpoint value. Offsets may or may not be acceptable for some industrial systems. The offset problem can be reduced by combining other modes of control with proportional controllers (Stephan, 1994).

### 2.6.3.3 Integral Control:

The output of a controller is used to actuate the final control element to eliminate any difference between the setpoint and actual values of an operating system. This difference is commonly called the \textit{error signal}. A controller is designed to eliminate system error. In proportional control, the output was adjusted proportionally to correct the system error. As a rule, this type of control produces an offset problem in the output.

An integral controller has an output whose rate of change is proportional to the system error signal. As long as there is an error, the output will continue to change to correct it. When the error is zero, the integral controller maintains the output at this value until a new error occurs. This means that an integral controller has inertia: It has a tendency to hold the output which was necessary to eliminate the error signal applied to its input.

Integral control is continuous, and the output changes at a rate proportional to the magnitude and duration of the error signal. When there is a large error signal, the output changes rapidly to correct the error. As the error gets smaller, the output changes more
slowly. This action is done to minimize the possibility of overcorrection. As long as there is an error, the output will continue to change. Mathematically, this is expressed as

\[
\frac{\Delta V_{\text{out}}}{\Delta t} = K_i \cdot V_e
\]

or

\[
\Delta V_{\text{out}} = K_i \cdot V_e \cdot \Delta t
\]

where \( \Delta V_{\text{out}} = \) controller output voltage
\( \Delta t = \) time rate of change
\( K_i = \) integration constant
\( V_e = \) error voltage

2.6.3.4 Derivative Control:

Many controllers have an inertia or \textit{hysteresis} problem. In the water temperature control system for example, it takes some time for steam to increase the temperature of the water. This means that there is a delay between the application of steam and the water temperature rising to a new value. The significance of this is that an error will not cause an immediate deviation from the setpoint value. When an error is detected by the system, it responds just as slowly to the corrective action. To overcome this sluggish characteristic, some exaggerated corrective action must be taken.

If a controller produces a large corrective signal in response to a minute error, the system will be brought into control more quickly. This occurs even if the system has a large amount of inertia. However, if the corrective action remains large, the controller will overcompensate for the error. This could cause the unit to break into oscillation. A more desirable corrective action is one that is initially large but drops off with time. This is a characteristic of the derivative controller.

A basic element of the derivative controller is a differentiator circuit. A differentiator works in proportion to the rate of change of its input.

Electronically, this is determined by the product of circuit resistance and capacitance. Mathematically, the output of a derivative controller is expressed as
\[ V_{out} = K_p \cdot \Delta V_e/\Delta t \]

where

\[ K_d = \text{derivative gain} \]
\[ \Delta V_e = \text{change in error voltage} \]
\[ \Delta t = \text{change in time rate} \quad \text{(Stephan, 1994).} \]

### 2.6.3.5 Proportional Plus Integral Plus Derivative Control:

When proportional, integral, and derivative control operations are combined, the PID controller is a unique instrument that is widely used to control a number of difficult processes with a great deal of precision. This type of controller is generally more expensive than other units, and it is more difficult to prepare for operation. In some instruments, each mode of operation can be selected for independent use by programming in the desired operation. Each mode of control must be individually adjusted or tuned to make it functional. PT and PD control can also be accomplished by instrument programming. PID controllers are generally not used for all controller applications today. Controller selection is determined by such things as the amount of precision control needed, the difficulty of the process being controlled, the initial set-up and tuning procedure, the characteristics of the process being controlled, and the initial cost of the controller (Gasmelseed, 2014).

### 2.6.4 Pressure Control:

Pressure control refers to those functions that alter the pressure level of an operating system. Such operations include relieving, reducing, bypassing, sequencing, and counterbalance. As a general rule, control devices of this type are named according to the function they achieve.

### 2.6.5 Flow Control:

The sensing elements of a flow meter are either of the inferential type or they deduce an output by direct displacement of quantities. The output signal of the sensing element may be either mechanical or electrical, depending on the type of sensor employed.
2.6.6 Sensors:
Sensor-element operation is an extremely important consideration when selecting a thermal system controller for a specific application. Such things as response time, temperature operating range, resolution sensitivity, and repeatability are dependent on the sensor element. In addition, the physical size of the sensor has a great deal to do with component location and installation design procedures.

2.6.7 Temperature Controllers:
Are used in heat systems to achieve the control function. A controller senses system temperature and decides on the amount of heat needed to meet the demands of the operating setpoint. Controller accuracy is determined by temperature gradients, thermal lag, component location, and controller selection.

2.6.8 Level control:
Equipment used to determine the level of a storage tank is based on the operating principle of the sensing element. This element is responsible for detecting a change in level and generating a signal that is used to correct the problem. In general, level systems will respond to either mechanical, pneumatic, electrical, radiation, or ultrasonic information (Patrick and Fardo, 2009).

2.7 Routh-Hurwitz Criterion:
The Routh-Hurwitz stability criterion provides a simple algorithm to decide whether or not the zeros of a polynomial are all in the left half of the complex plane (such a polynomial is called at times "Hurwitz"). A Hurwitz polynomial is a key requirement for a linear continuous-time invariant to be stable (all bounded inputs produce bounded outputs).
Necessary stability conditions: Conditions that must hold for a polynomial to be Hurwitz. If any of them fails - the polynomial is not stable. However, they may all hold without implying stability.

Sufficient stability conditions:
Conditions that if met imply that the polynomial is stable. However, a polynomial may be stable without implying some or any of them.

The Routh criteria provides conditions that are both necessary and sufficient for a polynomial to be Hurwitz.

The Routh-Hurwitz criteria is comprised of three separate tests that must be satisfied. If any single test fails, the system is not stable and further tests need not be performed. For this reason, the tests are arranged in order from the easiest to determine to the hardest.

The Routh Hurwitz test is performed on the denominator of the transfer function, the **characteristic equation**. For instance, in a closed-loop transfer function with \( G(s) \) in the forward path, and \( H(s) \) in the feedback loop, we have:

\[
T(s) = \frac{G(s)}{1 + G(s)H(s)}
\]

If we simplify this equation, we will have an equation with a numerator \( N(s) \), and a denominator \( D(s) \):

\[
T(s) = \frac{N(s)}{D(s)}
\]

The Routh-Hurwitz criteria will focus on the denominator polynomial \( D(s) \).

**Rule 1**
All the coefficients \( a_i \) must be present (non-zero)

**Rule 2**
All the coefficients \( a_i \) must be positive (equivalently all of them must
be negative, with no sign change)

**Rule 3**

If **Rule 1** and **Rule 2** are both satisfied, then form a Routh array from the coefficients $a_i$. There is one pole in the right-hand s-plane for every sign change of the members in the first column of the Routh array (any sign changes, therefore, mean the system is unstable).

We will explain the Routh array below.

**The Routh Array**

The Routh array is formed by taking all the coefficients $a_i$ of $D(s)$, and staggering them in array form. The final columns for each row should contain zeros:

\[
\begin{array}{cccc}
 s^N & a^N & a^N - 2 & 0 \\
 s^{N-1} & a^{N-1} & a^N - 3 & 0 \\
 s^{N-2} & & & \\
 s^{N-3} & & & \\
 s^0 & & & \\
 \end{array}
\]

Therefore, if $N$ is odd, the top row will be all the odd coefficients. If $N$ is even, the top row will be all the even coefficients. We can fill in the remainder of the Routh Array as follows:

\[
\begin{array}{cccccccc}
 s^N & a^N & a^N - 2 & 0 \\
 s^{N-1} & a^{N-1} & a^N - 3 & 0 \\
 s^{N-2} & b^N - 1 & b^N - 3 & \ldots \\
 s^{N-3} & c^N - 1 & c^N - 3 & \ldots \\
 s^0 & & & \\
 \end{array}
\]

Now, we can define all our $b$, $c$, and other coefficients, until we reach row $s^0$. To fill them in, we use the following formulae:

\[
bN - 1 = \frac{-1}{a^{N-1}} \begin{vmatrix} a^N & aN - 2 \\ aN - 1 & aN - 3 \end{vmatrix}
\]

And

\[
bN - 3 = \frac{-1}{a^{N-1}} \begin{vmatrix} a^N & aN - 4 \\ aN - 1 & aN - 5 \end{vmatrix}
\]
For each row that we are computing, we call the left-most element in the row directly above it the pivot element. For instance, in row b, the pivot element is $a_{N-1}$, and in row c, the pivot element is $b_{N-1}$ and so on and so forth until we reach the bottom of the array.

To obtain any element, we negate the determinant of the following matrix, and divide by the pivot element:

\[
\begin{vmatrix}
k & m \\
l & n
\end{vmatrix}
\]

Where:

- $k$ is the left-most element two rows above the current row.
- $l$ is the pivot element.
- $m$ is the element two rows up, and one column to the right of the current element.
- $n$ is the element one row up, and one column to the right of the current element (Hurwitz, 1964).

In terms of $k \ l \ m \ n$, our equation is:

\[
\nu = \frac{(lm)-(kn)}{l}
\]

2.8 Root Locus:

The root locus is a graphical representation in s-domain and it is symmetrical about the real axis. Because the open loop poles and zeros exist in the s-domain having the values either as real or as complex conjugate pairs. In this chapter, let us discuss how to construct (draw) the root locus. In control theory and stability theory, root locus analysis is a graphical method for examining how the roots of a system change with variation of a certain system parameter, commonly a gain within a feedback system. This is a technique used as a stability criterion in the field of classical control theory developed by Walter R. Evans which can determine stability of the system. The root locus plots the poles of the closed loop transfer function in the complex s-plane as a function of a gain parameter. In addition to determining the stability of the system, the root locus can be used to design the damping ratio ($\zeta$) and natural frequency ($\omega_n$) of a feedback system. Lines of constant natural frequency can be drawn radially from the
origin and lines of constant damping ratio can be drawn as arccosine whose center points coincide with the origin. By selecting a point along the root locus that coincides with a desired damping ratio and natural frequency, a gain $K$ can be calculated and implemented in the controller. More elaborate techniques of controller design using the root locus are available in most control textbooks: for instance, lag, lead, PI, PD and PID controllers can be designed approximately with this technique. The definition of the damping ratio and natural frequency presumes that the overall feedback system is well approximated by a second order system; i.e. the system has a dominant pair of poles. This is often not the case, so it is good practice to simulate the final design to check if the project goals are satisfied.

Plotting Root locus using Matlab:

Matlab format:

```matlab
>>num=[ ];
>>den=[ ];
>>sys=tf( );
>>rlocus( )
```

Where:

- `rlocus(sys)`: calculate and plots the root locus of the open-loop SISO model `sys`.
- `tf`: computes the transfer function
- `num`: The numerator of the transfer function
- `den`: the denominator of the transfer function

![Matlab graph of root locus](image)

**Fig 2.9 Matlab graph of root locus**
2.9 Bode plot:

A Bode Plot is a useful tool that shows the gain and phase response of a given LTI system for different frequencies. Bode Plots are generally used with the Fourier Transform of a given system. The frequency of the bode plots are plotted against a logarithmic frequency axis. Every tickmark on the frequency axis represents a power of 10 times the previous value. For instance, on a standard Bode plot, the values of the markers go from (0.1, 1, 10, 100, 1000, ...) Because each tickmark is a power of 10, they are referred to as a decade. Notice that the "length" of a decade decreases as you move to the right on the graph.

The bode Magnitude plot measures the system Input/Output ratio in special units called decibels. The Bode phase plot measures the phase shift in degrees (typically, but radians are also used).

Plotting Bode plot with Matlab:

MATLAB format:
```
>>num=[ ];
>>den=[ ];
>>sys=tf(num,den);
>>bode(sys),grid
```

Where:

Bode(sys): plots the Bode diagram of the OLTDFig 2.10 Bode plot graph of Matlab
2.10 Ziegler-Nichole’s Method:

It is a heuristic method of tuning a PID controller. It was developed by John G. Ziegler and Nathaniel B. Nichols. It is performed by setting the I (integral) and D (derivative) gains to zero. The "P" (proportional) gain, Kp is then increased (from zero) until it reaches the ultimate gain Ku, at which the output of the control loop has stable and consistent oscillations. Ku and the oscillation period Tu are used to set the P, I, and D gains depending on the type of controller used:

1. First, note whether the required proportional control gain is positive or negative. To do so, step the input u up (increased) a little, under manual control, to see if the resulting steady state value of the process output has also moved up (increased). If so, then the steady-state process gain is positive and the required Proportional control gain, Kc, has to be positive as well.

2. Turn the controller to P-only mode, i.e. turn both the Integral and Derivative modes off.

3. Turn the controller gain, Kc, up slowly (more positive if Kc was decided to be so in step 1, otherwise more negative if Kc was found to be negative in step 1) and observe the output response. Note that this requires changing Kc in step increments and waiting for a steady state in the output, before another change in Kc is implemented.

4. When a value of Kc results in a sustained periodic oscillation in the output (or close to it), mark this critical value of Kc as Ku, the ultimate gain. Also, measure the period of oscillation, Pu, referred to as the ultimate period. (Hint: for the system A in the PID simulator, Ku should be around 0.7 and 0.8)

5. Using the values of the ultimate gain, Ku, and the ultimate period, Pu, Ziegler and Nichols prescribes the following values for Kc, ti and td, depending on which type of controller is desired:
### Table 2.2 Ziegler-Nichols Tuning parameters

<table>
<thead>
<tr>
<th></th>
<th>$K_c$</th>
<th>$t_I$</th>
<th>$t_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P control</td>
<td>$K_u/2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI control</td>
<td>$K_u/2.2$</td>
<td>$P_u/1.2$</td>
<td></td>
</tr>
<tr>
<td>PID control</td>
<td>$K_u/1.7$</td>
<td>$P_u/2$</td>
<td>$P_u/8$</td>
</tr>
</tbody>
</table>

#### 2.11 P, I, D controllers:

Proportional-Integral-Derivative (PID) control is the most common control algorithm used in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. As the name suggests, PID algorithm consists of three basic coefficients; proportional, integral and derivative which are varied to get optimal response. Closed loop systems, the theory of classical PID and the effects of tuning a closed loop control system are discussed in this paper. The PID toolset in LabVIEW and the ease of use of these VIs is also discussed.

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2.11.1 Control System:

The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating proportional, integral, and derivative responses and summing those three components to compute the output. Before we start to define the parameters of a PID controller, we shall see what a closed loop system is and some of the terminologies associated with it.

2.11.2 PID Theory:

2.11.2.1 Proportional Response:

The proportional component depends only on the difference between the set point and the process variable. This difference is referred to as the Error term. The proportional gain ($K_c$) determines the ratio of output response to the error signal. For instance, if the error term has a magnitude of 10, a proportional gain of 5 would produce a proportional response of 50. In general, increasing the proportional gain will increase the speed of the control system response. However, if the proportional gain is too large, the process variable will begin to oscillate. If $K_c$ is increased further, the oscillations will become larger and the system will become unstable and may even oscillate out of control.

2.11.2.2 Integral Response:

The integral component sums the error term over time. The result is that even a small error term will cause the integral component to increase slowly. The integral response will continually increase over time unless the error is zero, so the effect is to drive the Steady-State error to zero. Steady-State error is the final difference between the process variable and set point. A phenomenon called integral windup results when integral action saturates a controller without the controller driving the error signal toward zero.

2.11.2.3 Derivative Response:

The derivative component causes the output to decrease if the process variable is increasing rapidly. The derivative response is proportional to the rate of change of the
process variable. Increasing the derivative time ($T_d$) parameter will cause the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response. Most practical control systems use very small derivative time ($T_d$), because the Derivative Response is highly sensitive to noise in the process variable signal. If the sensor feedback signal is noisy or if the control loop rate is too slow, the derivative response can make the control system unstable

### 2.11.2.4 Tuning:

The process of setting the optimal gains for P, I and D to get an ideal response from a control system is called tuning. There are different methods of tuning of which the “guess and check” method and the Ziegler Nichols method will be discussed. The gains of a PID controller can be obtained by trial and error method. Once an engineer understands the significance of each gain parameter, this method becomes relatively easy. In this method, the I and D terms are set to zero first and the proportional gain is increased until the output of the loop oscillates. As one increases the proportional gain, the system becomes faster, but care must be taken not make the system unstable. Once P has been set to obtain a desired fast response, the integral term is increased to stop the oscillations. The integral term reduces the steady state error, but increases overshoot. Some amount of overshoot is always necessary for a fast system so that it could respond to changes immediately. The integral term is tweaked to achieve a minimal steady state error. Once the P and I have been set to get the desired fast control system with minimal steady state error, the derivative term is increased until the loop is acceptably quick to its set point. Increasing derivative term decreases overshoot and yields higher gain with stability but would cause the system to be highly sensitive to noise. Often times, engineers need to tradeoff one characteristic of a control system for another to better meet their requirements (Agarwal, [www.elprocus.com](http://www.elprocus.com)).
Chapter Three

Materials and Methods

3.1 Air cooled Heat exchanger:

The hot process fluid to be cooled flows through a tube while the cooling air flows across the outer surface to remove heat. The cooling air is propelled by fans in either a forced draft or induced draft configuration. Specially designed fins are attached to the outer surface of the tube to create a large surface area for more effective cooling. The heat transfer rate is a function of the fins’ surface area and the velocity of the air flow.

The mechanical design of the exchanger must accommodate the process conditions including pressure and temperature and, possibly, corrosivity, fouling and condensation.

In the plant, the Air cooled heat exchanger consists of many sides and blowers, which lead to difference in capacity according to vapour quantity. Basically it depends on air cooling and has a spray water option in case of need a further cooling in hot days.

Fig (3.1-3.2) Air cooled Heat Exchanger.
(Source: Khartoum Petrochemical co. Plant, 2018)
In this study we will simplify equipments and suppose unit consists of one fractionation tower, one heat exchanger consisting of one blower and two sides, and finally a reflux drum.

### 2.2 MATLAB for Control Systems Design and Analysis:
MATLAB is a programming language that is specially designed for the manipulation of matrices. Because of its computational power, MATLAB is a tool of choice for many control engineers to design and simulate control systems. MATLAB has a number of plug-in modules called “Tool boxes”.

#### 2.2.1 Design and Analysis Function:
MATLAB has several functions that are useful for designing and analyzing linear systems. These function can be used in both continues and discrete time systems. The basic design and analysis function a summarized below:

- `rlocus` Evans root-locus plot
- `rlocfind` Locating the system gain from pole location indicated be the mouse.
- `Nyquist` Nyquist frequency response plot
- `Bode` Log-magnitude and phase vs. frequency response plot
- `Step` Unit step time response plot
- `C2d` Convert from continues time to discrete time model
- `D2c` Convert from discrete time to continues time model

#### 2.2.2 How to Use the Step Command
To start MATLAB on a MS windows system, double-click on the MATLAB icon. MATLAB displays the prompt (>>) to indicate that it is ready to receive instructions. To create M-files in the Command window, select New from the file menu, and then select M-file. Type in the file when finished; select Save from the File menu.

Consider a first order transfer function \( G(s) = \frac{1}{1+s} \)

The root locus can be created by enter the transfer function to MATLAB as follow:

```matlab
num = [1];
```
den=[1 1];
sys=tf(num,den)
rlocus(sys),grid

where num=[1] is a numerator (k=1) and den = [1 1] represent the ‘s’ coefficients and the ‘s^0’ coefficient respectively. Tf (num,den) create the transfer function. rlocus (sys) Evans root locus plot and grid produces a rectangular grid on plot. It is also possible, using a cursor in the graphics window, to select a point on the locus, and return values for open-loop gain k and closed-loop poles using the command [k,poles] = rlocfind (num,den) (Ronald, 2001).

3.3 Distillation Column Design:

![Distillation Column Diagram](image)

Feed of LPG to dist. Tower = 10000 kg/hr

Top of tower temp. = 46°C, Top of press. = 1.68 Mpa

Bottom of tower temp. = 104°C, Tower press. = 1.76 Mpa
3.3.1 Feed compositions and Keys (LK-HK):

Table 3.1 LPG feed composition

<table>
<thead>
<tr>
<th>No.</th>
<th>Component</th>
<th>% wt</th>
<th>M. wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C₂H₄</td>
<td>0.15</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>C₃H₆</td>
<td>30</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>C₃H₈</td>
<td>6.5</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>C₄H₁₀</td>
<td>23</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>C₄H₆</td>
<td>0.35</td>
<td>54</td>
</tr>
<tr>
<td>6</td>
<td>C₄H₈</td>
<td>40</td>
<td>56</td>
</tr>
</tbody>
</table>

-C₃H₆ the lowest wt. in bottom (0.05%) so it’s the (LK).
-C₄H₁₀ the lowest wt. in top (0.01%) so it’s the (HK).

Material balance:

\[ F = D + B \quad \rightarrow \quad F \times f_i = D \times d_i + B \times b_i \]

Basis: 100 t/hr

Lk = 100 * 0.30 = dᵢ + 0.05B \rightarrow 30 = dᵢ + 0.05

HK = 100 * 0.23 = 0.01D + bᵢ \rightarrow 23 = 0.01D + bᵢ

Lₙk = bᵢ = 0 \rightarrow fᵢ = dᵢ

Hₙk = dᵢ = 0 \rightarrow fᵢ = bᵢ

Table 3.2 Components Fractions Balance

<table>
<thead>
<tr>
<th>Component</th>
<th>Fᵢ</th>
<th>Dᵢ</th>
<th>Bᵢ</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂H₄</td>
<td>0.15</td>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>30</td>
<td>30-0.05B</td>
<td>0.05B</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>6.5</td>
<td>6.5</td>
<td>0</td>
</tr>
<tr>
<td>C₄H₁₀</td>
<td>23</td>
<td>0.01D0</td>
<td>23-0.01D</td>
</tr>
<tr>
<td>C₄H₆</td>
<td>0.35</td>
<td>0</td>
<td>0.35</td>
</tr>
<tr>
<td>C₂H₈</td>
<td>40</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>D=∑dᵢ</td>
<td>B=∑bᵢ</td>
</tr>
</tbody>
</table>
\[ D = 36.65 - 0.05B + 0.01D, \quad 0.99D = 36.65 - 0.05B \]

But \( F = B + D \rightarrow 100 = D + B \rightarrow B = 100 - D \)

\[ 0.99 D = 36.65 - 0.05(100-D) \]

\[ 0.99D - 0.05D = 31.65 \quad \therefore D = 33.67 \quad \therefore B = 100 - 33.67 = 66.32 \quad \text{But } F = 10000 \text{kg/hr} \]

\[ \therefore D = 10000/100 \times 33.67 = 3367 \text{kg/hr} \]

\[ B = 6632 \text{kg/hr} \]

For LK:

\[ d_{LK} = (30/100) \times 10^4 - 0.05 \times 6632 = 3000 - 331.6 = 2668.4 \text{ kg/hr} \]

\[ \therefore b_{LK} = (30/100) \times 10^4 - 2668.4 = 331.8 \text{ kg/hr} \]

For Hk:

\[ d_{Hk} = 0.01 \times 33.67 = 0.3367 \text{ kg/hr} \]

\[ b_{Hk} = 23/100 \times 10^4 - 0.01 \times 33.67 = 2299.6 \text{ kg/hr} \]

### 3.3.2 Calculations of mole fractions:

Wt of comp. 1 = \( 10^4 \times 0.0015 = 15 \text{ kg/hr} \)

Wt of comp. 2 = \( 10^4 \times 0.30 = 3000 \text{ kg/hr} \)

Wt of comp. 3 = \( 10^4 \times 0.065 = 650 \text{ kg/hr} \)

Wt of comp. 4 = \( 10^4 \times 0.23 = 2300 \text{ kg/hr} \)

Wt of comp. 5 = \( 10^4 \times 0.0035 = 35 \text{ kg/hr} \)

Wt of comp. 6 = \( 10^4 \times 0.40 = 4000 \text{ kg/hr} \)

Mol. Of comp. 1 = \( 15/28 = 0.53 \text{ mol/hr} \)

Mol. Of comp. 2 = \( 3000/42 = 71.4 \text{ mol/hr} \)

Mol. Of comp. 3 = \( 650/44 = 14.7 \text{ mol/hr} \)

Mol. Of comp. 4 = \( 2300/58 = 39.6 \text{ mol/hr} \)

Mol. Of comp. 5 = \( 35/54 = 0.64 \text{ mol/hr} \)

Mol. Of comp. 6 = \( 4000/56 = 71.4 \text{ mol/hr} \)
Total moles =198.3 mol/hr

Mole fractions:
1- 0.53/198.3=0.0026  
2- 71.4/198.3= 0.36  
3-14.7/198.3 = 0.074
4- 39.6/198.3=0.199  
5- 0.64/198.3= 0.003  
6-71.4/198.3= 0.36

Table 3.3 Mole Fractions of stream

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>D</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Mi</td>
<td>Wif</td>
<td>fi</td>
</tr>
<tr>
<td>1</td>
<td>28</td>
<td>15</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>3000</td>
<td>71.4</td>
</tr>
<tr>
<td>3</td>
<td>48</td>
<td>650</td>
<td>14.7</td>
</tr>
<tr>
<td>4</td>
<td>58</td>
<td>2300</td>
<td>39.6</td>
</tr>
<tr>
<td>5</td>
<td>54</td>
<td>35</td>
<td>0.64</td>
</tr>
<tr>
<td>6</td>
<td>56</td>
<td>4000</td>
<td>71.4</td>
</tr>
<tr>
<td>∑</td>
<td>10000</td>
<td>198.27</td>
<td>1.00</td>
</tr>
</tbody>
</table>

3.3.3 Number of trays calculations:

Dew Point and Bubble point

To calculate dew point temp. Take (Yi=XiD)  T=46c

Xi1=0.0067/3.6 =0.0018  
Xi2= 0.8/1.01 = 0.8  
Xi3= 0.187/0.9 =0.199
Table 3.4 bubble point calculation

<table>
<thead>
<tr>
<th>Comp.</th>
<th>C2H4</th>
<th>C3H6</th>
<th>C3H8</th>
<th>C4H10</th>
<th>C4H6</th>
<th>C4H8</th>
</tr>
</thead>
<tbody>
<tr>
<td>XiD</td>
<td>0.0067</td>
<td>0.8</td>
<td>0.187</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>K</td>
<td>3.6</td>
<td>1.02</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$\sum x_i = 1.009 \quad \therefore$ Dew point press. = 2Mpa from the chart

To get bubble pt. pressure we use Antoine eq. (Tb=104+273)

Table 3.5 Obtained Antoine Constants

<table>
<thead>
<tr>
<th></th>
<th>C2H4</th>
<th>C3H6</th>
<th>C3H8</th>
<th>C4H10</th>
<th>C4H6</th>
<th>C4H8</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.966</td>
<td>7.016</td>
<td>7.018</td>
<td>7.00</td>
<td>7.27</td>
<td>8.03</td>
</tr>
<tr>
<td>B</td>
<td>649.8</td>
<td>860.992</td>
<td>889.8</td>
<td>1022.08</td>
<td>1169.6</td>
<td>1013.6</td>
</tr>
<tr>
<td>C</td>
<td>262.7</td>
<td>255.89</td>
<td>257.084</td>
<td>248.145</td>
<td>255.54</td>
<td>250.29</td>
</tr>
</tbody>
</table>

$P_{vi} = \text{Exp}[6.966-(649.8/262.7+104)]$

$A_p = \text{Amm Hg} + 2.124903 = 6.966+2.124903= 9.09 \rightarrow$

$log P_{v1} = [9.09-649.8/(262.7-273+104+273.15) =$

$9.09*2.3025=20.93 \quad , \quad 649.8*2.3025=1496.22$

$\ln P_{v1} = [20.93-1496.22/(377-10.45)] = 16.85 \quad \therefore P_{v1} = 20.79\text{Mpa} \quad , \quad K_1 = 20.79/1.75 = 11.8$

$P_{v2} = \text{Exp}[7.016-860.992/(255.89+377.15)] \quad A_p = 7.016+2.124 = 9.14$

$log P_{v2} = 9.14-860.992/(377.15-17.26)$

$9.14*2.3=21.04 \quad , \quad 860.992*2.3=1982.43$

$\ln P_{v2} = 14.54 \quad \therefore P_{v2} = 2.063 \text{Mpa} \quad K_2 = 1.17$

$P_{v3} = \text{Exp}[7.018-889.8/(257.084+104)] \quad A_p = 7.018+2.124 = 9.14$

$log P_{v3} = [9.14-889.8/(377.15-16.15)] \quad 9.14*2.3=21.04 \quad , \quad 889.8*2.3=2048.76$

$\ln P_{v3} = 15.36 \quad P_{v3} = 4.68\text{Mpa} \quad K_3 = 2.67$

$P_{v4} = \text{Exp}[7.00-1022.48/(248.145+104)]$

$P_{v4 \text{pa}} = 7.00+2.124=9.12 \quad , \quad 9.12*2.3=21 \quad , \quad 1022.48*2.3=2354.2$

$\ln P_v = [21-2354.2/352.14]$
\[ \ln P_{v4} = 14.31 \quad P_{v4} = 1.63 \text{Mpa} \quad k_4 = 0.93 \]

\[ P_{v5} = \exp\left[7.27-1169.6/(255.54+104)\right] \]

\[ 7.27 + 2.124 = 9.39 \quad 9.39 \times 2.3 = 21.6 \quad 1169.6 \times 2.3 = 2693 \]

\[ \ln P_{v5} = \left[\frac{21.62-2693}{359.54}\right] = 14.12 \]

\[ P_{v5} = 1.35 \text{Mpa} \quad k_5 = 0.77 \]

\[ P_{v6} = \exp\left[7.03-1013.6/(250.3+104)\right] \]

\[ 7.03 + 2.124 = 9.15 \quad 9.15 \times 2.3 = 21.06 \quad 1013.6 \times 2.3 = 2333.8 \]

\[ \ln P_{v2} = \left[\frac{21.06-2333.8}{354.3}\right] = 14.14 \]

\[ P_{v6} = 1.79 \text{Mpa} \quad k_6 = 1.02 \]

**Table 3.6 Dew point calculation**

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>XiB</th>
<th>Yi</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.88</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1.17</td>
<td>0.069</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>2.67</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0.93</td>
<td>0.33</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>0.77</td>
<td>0.005</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>1.02</td>
<td>0.595</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sum Y_i = 0.98 \approx 1.00 \]

\[ P_{i1} = P_{v1} \times X_1 = 20.79 \times 0.0067 = 0.13 \]

\[ P_{i2} = 2 \times 0.8 = 2.6 \quad P_{i3} = 4.68 \times 0.18 = 0.87 \quad P_{i4} = 1.63 \times 0 = 0 \quad P_{i5} = 1.35 \times 0 = 0 \]

\[ P_{tB} = \sum P_i \quad \therefore P_{tB} = 2.6 \text{ Mpa} \]

From Deprister chart we obtained Ki for each component and dew pt. press. = 2 Mpa

From Antoine eq. obtained Pvi then get Ptb

\[ \sum P_{vi} = P_{tB} = 2.6 \text{ Mpa} \]

\[ T_f = (T_i + T_B)/2 = (46 + 104)/2 = 75 \text{c} \quad P_f = (P_t + P_B)/2 = (2.6 + 2)/2 = 2.3 \]
Table 3.7 Average Relative Volatility of Stream Components

<table>
<thead>
<tr>
<th>Tower Temp. C</th>
<th>Top</th>
<th>Feed</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press. Mpa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46c</td>
<td>24Mpa</td>
<td>75c</td>
<td>2.3Mpa</td>
</tr>
<tr>
<td>I</td>
<td>Ki</td>
<td>αi</td>
<td>Ki</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>1.16</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.33</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>3.1</td>
<td>1.03</td>
<td>4.8</td>
</tr>
<tr>
<td>5</td>
<td>3.1</td>
<td>1.03</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>0.42</td>
<td>0.14</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Kj Top=3 , Kj feed=4.9 , Kj Bottom=7

α1=0.87 , α2=0.277 , α3=0.272 , α4=0.99 , α5=0.99 , α6=0.43

N min = ln (xlk/xhk)D * (xhk/xlk)B / lnαlk

N min= 9 plates

3.3.4 Minimum and actual reflux ratio:

By Mcabe Thiele method we obtain R , R min

Rmin= 1.92 , R=1.28

3.3.5 Ideal number of trays:

X= R-Rmin / R+1 = (1.92-1.28)/(1.92+1) =0.219

Y=1-x^(1/3) = 1-(0.29)^(1/3) = 0.397

N=(N min + y) / (1-y ) = 15.5 ≈ 16 plate

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3.3.6 Feed Plate Location:

\[ \frac{n}{m} = \left[ \frac{B}{D} \times \frac{x_{nk}}{x_{lk}}F \times \left(\frac{x_{lb}}{x_{hk}D}\right)^2 \right]^{0.206} \]

\[ B = 119.59 \quad , \quad D = 78.37 \quad , \quad x_{hk}F = 0.2 \quad , \quad x_{lB} = 0.066 \quad , \quad x_{lF} = 0.37 \quad , \quad x_{hD} = 0.00006 \]

\[ \therefore \frac{n}{m} = 17.3 \quad n + m = 16 \quad \therefore m = 16 - n \rightarrow n/16 - n = 17.3 \]

\[ \therefore n = 15 \quad , \quad m = 1 \]
Chapter Four

Results and Discussion

4.1 Control strategy:

4.1.1 At the top of column:

- Controlled variables at the top are, Reflux drum level (L), Top composition (xd).
- Manipulated variables are, Feed rate (F), Reflux rate (R).

\[-m_1= \text{Refux rate (R)}, \quad m_2= \text{Feed rate (F)}\]

\[-Y_1= \text{level at reflux drum (L)}, \quad Y_2= \text{top composition (xd)}\]

- Transfer functions: \(k_{11} = \frac{4}{0.1s+1}\), \(k_{12} = \frac{0.103}{0.15s+1}\), \(k_{21} = \frac{5}{25+0.2}\), \(k_{22} = \frac{100}{0.2s+1}\)

\[
\lambda_{11} = \frac{1}{1-\left(\frac{k_{12}k_{21}}{k_{11}k_{22}}\right)} = \frac{1}{1-(2.5*0.103)/400} = 1.0064
\]

\[
\begin{pmatrix}
    4 & 0.103 \\
    25 & 100
\end{pmatrix}
\]

Fig 4.1 Block diagram (top section)
4.1.2 Control strategy of bottom section:

- Controlled variables are: Base level at the bottom (L), Bottom composition (xb)

- Manipulated variables are: Feed rate (F), Steam rate (S)

\[ m_1 = \text{feed rate (F)} , \ m_2 = \text{steam rate (S)} \]

\[ Y_1 = \text{level at the bottom (L)}, \ Y_2 = \text{bottom composition (xb)} \]

- Transfer functions are: 
  \[ H_{11} = \frac{0.2}{0.2s+1} , \ H_{12} = \frac{(2e^{-0.5}s)}{(0.5s+1)} , \ H_{21} = \frac{(0.1e^{-1.3}s)}{(s+1)} , \ H_{22} = \frac{5}{(3s+1)(2s+1)} \]

\[ \begin{bmatrix} F \\ S \end{bmatrix} L \]

\[ \begin{bmatrix} F \\ \lambda = 1.67 \\ S \end{bmatrix} \]

\[ \begin{bmatrix} \lambda = -0.67 \\ 2 \\ 2.5 \end{bmatrix} \]

\[ \begin{bmatrix} F \\ S \end{bmatrix} \]

\[ \begin{bmatrix} F \\ \lambda = 1.67 \\ S \end{bmatrix} \]

\[ \begin{bmatrix} \lambda = -0.67 \\ 0.2 \\ 0.1 \end{bmatrix} \]

\[ \begin{bmatrix} F \\ S \end{bmatrix} \]

\[ \begin{bmatrix} \lambda = 1.67 \\ -0.67 \end{bmatrix} \]

\[ \begin{bmatrix} L \\ xb \end{bmatrix} \]

\[ \begin{bmatrix} L \\ xb \end{bmatrix} \]
Fig 4.3 Block diagram (bottom section)

Fig 4.4 Physical diagram (bottom section)
4.2 Loops stability and analysis:

4.2.1 Loop1-top section:

Transfer functions: \( G_c = K_c \), \( G_v = \frac{2}{0.2s+1} \), \( G_p = \frac{5}{(2s+1)(s+1)} \), \( G_m = \frac{1}{0.1s+1} \)

![Fig 4.5 loop1 block diagram](image)

System stability: **Ruoth-Herwitz Array**:

\[
\text{OLT}\!F = K_c \times \frac{2}{0.2s+1} \times \frac{5}{(2s+1)(s+1)} \times \frac{1}{0.1s+1} = \frac{10K_c}{(0.2s+1)(2s+1)(s+1)(0.1s+1)} = \frac{10K_c}{(0.04s^4+0.66s^3+2.92s^2+3.3s+1)}
\]

Characteristic eq. = \( 0.04s^4+0.66s^3+2.92s^2+3.3s+1 + 10K_c = 0 \)

\[
\begin{array}{cc}
b_1 & b_2 \\
c_1 & c_2 \\
d_1 & d_2 \\
0.04 & 2.92 & 1+10K_c \\
0.66 & 3.3 & 0 \\
\end{array}
\]

\( b_1 = 2.72, b_2 = 1+10K_c, c_1 = 3.06-2.42K_c, c_2 = 0 \)

\( d_1 = 1+10K_c \)

Direct sub.:

\( \omega, K_u, P_u \)
\[ 0.04s^4 + 0.66s^3 + 2.92s^2 + 3.3s + 1 + 10kc = 0, \text{ Put } S = (iw), i^2 = -1 \]
\[ 0.04(iw)^4 + 0.66s^3 + 2.92(iw)^2 + 3.3(iw) + 1 + 10kc = 0 \]
\[ 0.04w^4 - 0.66iw^3 - 2.92w^2 + 3.3iw + 1 + 10kc = 0 \]

Take imaginary Part: 
\[ -0.66iw^3 + 3.3iw = 0 \]
\[ \rightarrow w^2 = 5, w = 2.23 \text{ rad/sec} \]

Pu = 2\pi/2.23 = 2.8 sec

Real part: 
\[ 0.04w^4 - 2.92w^2 + 1 + 10kc = 0 \]
\[ -12.5 + 10kc = 0 \]
\[ \rightarrow kc = 1.25 \quad \therefore \text{ system is stable.} \]

### 4.2.2 Loop2:

Transfer functions: 
\[ G_c = Kc, \quad G_v = \frac{1}{0.3s+1}, \quad G_p = \frac{0.1}{4s+1}, \quad G_m = \frac{1}{0.2s+1} \]

\[ \text{Fig 4.6 loop2 block diagram} \]

System stability:

**Routh Array:**  
\[ \text{OLT} = \frac{0.1Kc}{(0.3s+1)(4s+1)(0.2s+1)} \]

\[ 0.1Kc/(1.2s^2 + 4s + 0.3s + 1)(0.2s + 1) = 0.1Kc/(0.24s^3 + 2.06s^2 + 4.5s + 1) \]

\[ \therefore \text{ Charc. Eq.} = 0.24s^3 + 2.06s^2 + 4.5s + 1 + 0.1Kc = 0 \]

\[ \begin{array}{c|cc}
0.24 & 4.5 & 0 \\
2.06 & 1+0.1Kc & 0 \\
\end{array} \]

\[ b_1 = 4.38 - 0.01Kc \rightarrow kc = 365 \]

\[ b_1 \quad c_1 \]

\[ b_2 \quad c_2 \]

**Direct sub.:**  
\[ 0.24s^3 + 2.06s^2 + 4.5s + 1 + 0.1Kc = 0 \]

\[ S = (wi), i^2 = -1 \]
-0.24i (w^3) -2.06(w)^2 + 4.5iw +1 + 0.1kc = 0

Imag. Part: -0.24(w)^2 + 4.5 = 0 \implies w^2 = 18.75 \rightarrow w = 4.33 \text{ rad/sec.} \quad \text{Pu} = 2\Pi/4.33 = 1.45 \text{ sec.}

Real part: -2.06 w^2 + 1 + 0.1kc = 0 \quad \text{kc} = 37.6/0.1 = 376 \quad \therefore \text{system is stable.}

### 4.2.3 Loop3 (bottom section):

Transfer functions:

- \( G_c = K_c \)
- \( G_v = 1/(2s+1) \)
- \( G_p = 0.2/(0.5s+1) \)
- \( G_m = 1/(3s+1) \)

\[
\begin{align*}
\text{Ysp} & \rightarrow \left( \begin{array}{c} K_c \\ 1/(2s+1) \\ 0.2/(0.5s+1) \\ 1/(3s+1) \end{array} \right)
\end{align*}
\]

\text{Fig 4.7 loop 3 block diagram}

\text{OLTF} = 0.2kc/(2s+1)(0.5s+1)(3s+1)

\text{Charac. Eq.} = (s^2 + 2.5s + 1)(3s+1) + 0.2kc = 0

\[
\begin{align*}
3s^3 + 7.5s^2 + 3s + 1 + 2.5s + 1 + 0.2kc &= 0 \\
3s^3 + 8.5s^2 + 5.5s + 1 + 0.2kc &= 0
\end{align*}
\]

System stability:

\textbf{Routh Array:}

\[
\begin{array}{ccc}
3 & 5.5 & 0 \\
8.5 & 1 + 0.2kc & b1 = 5.14 - 0.07kc \\
b1 & c1 & \therefore K_c = 73.4 \quad \text{system is stable} \\
b2 & c2
\end{array}
\]
Direct sub. :

\[3s^3 + 8.5s^2 + 5.5s + 1 + 0.2kc = 0\]

\[-3iw^3 - 8.5w^2 + 5.5iw + 1 + 0.2kc = 0\]

Imag. part: \[-3iw^3 + 5.5iw = 0\] \(w^2 = 1.83 \rightarrow w = 1.35\) rad/sec

\[
\therefore Pu = 2\pi/1.35 = 4.56\text{sec.}
\]

Real part: \[-8.5w^2 + 1 + 0.2kc = 0\] \(Kc = 72.4\)

4.2.4 Loop4:

Transfer functions: \(G_c = Kc\), \(G_v = 2/(0.5s + 1)\), \(G_p = 1.5/(0.1s + 1)\), \(G_m = 1/(1.5s + 1)\)

\[
\text{OLTF} = \frac{3kc}{(0.5s + 1)(0.1s + 1)(1.5s + 1)}
\]

\[(0.05s^2 + 0.7s + 2)(1.5s + 1) + 3kc = 0\]

\[0.075s^3 + 1.1s^2 + 3.7s + 2 + 3kc = 0\]

Routh Array:

<table>
<thead>
<tr>
<th></th>
<th>0.075</th>
<th>3.7</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1</td>
<td>2+3kc</td>
<td></td>
</tr>
<tr>
<td>b1</td>
<td>c1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b2</td>
<td>c2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[b_1 = 3.56 - 0.2kc\]

\[kc = 17.8 \quad \text{system is stable}\]
Direct sub:

\[0.075s^3+1.1s^2+3.7s+2+3kc=0, \quad s=(iw), \quad i^2=-1\]

\[-0.075iw^3-1.1w^2+3.7iw+2+3kc=0\]

\[-0.075w^2+3.7=0 \rightarrow w^2=49.3 \quad w=7.02\text{rad/sec} \quad Pu=0.89\text{sec}\]

Real part: \[-1.1w^2+2+3kc=0\]

\[Kc=17.41\]

**4.2.5 Applying the Root – locus using MATLAB (loop1):**

OLTФ was taken, use MATLAB to plot Root – locus and obtain the ultimate gain (Ku), ultimate period (Pu), and frequency (w).

\[\text{OLTФ}= 10Kc/(0.04s^4+0.66s^3+2.92s^2+3.3s+1)\]

Matlab format:

```matlab
num=[10];
den=[.04 .66 2.92 3.3 1];
sys=tf(num,den);
rlocus(sys)
```
the results of Root – locus in MATLAB are:

\[ K_c = 1.28, \quad \omega = 2.25, \quad Pu = \frac{2\pi}{2.25} = 2.8\text{sec} \]

### 4.2.6 Bode plot method of loop1

To determine the ultimate gain\((K_u)\), ultimate period\((Pu)\) using MATLAB:

\[ 10K_c/(0.04s^4+0.66s^3+2.92s^2+3.3s+1)=0 \]

MATLAB format:

```matlab
num=[10];
den=[.04 .66 2.92 3.3 1];
sys=tf(num,den);
bode(sys),grid
```
At $-180^\circ$, $\omega_c = 2.37\text{rad/sec}$

$P_u = 2\pi/2.37$

The ultimate period $P_u = 2.65$

Magnitude $= -3.06$ \implies 20$\log_{10}$Ar $= -3.06$

$Ar = 0.7 \implies Ku = 1/0.7 = 1.43$

**Table 4.1 Summary of loop 1**

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate gain Ku</th>
<th>Ultimate period Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh–Herwitz</td>
<td>1.26</td>
<td>2.8</td>
</tr>
<tr>
<td>Direct sub.</td>
<td>1.25</td>
<td>2.8</td>
</tr>
<tr>
<td>Root locus</td>
<td>1.27</td>
<td>2.8</td>
</tr>
<tr>
<td>Bode plot</td>
<td>1.43</td>
<td>2.65</td>
</tr>
<tr>
<td>Average</td>
<td>1.3</td>
<td>2.762</td>
</tr>
</tbody>
</table>
### Table 4.2 (Z-N) stability and tuning system of average of loop 1

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Gain ( K_c )</th>
<th>Integration time ( \tau_i )</th>
<th>Derivation time ( \tau_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.65</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>PI</td>
<td>0.585</td>
<td>2.4</td>
<td>_</td>
</tr>
<tr>
<td>PID</td>
<td>0.78</td>
<td>1.4</td>
<td>0.34</td>
</tr>
</tbody>
</table>

#### 4.2.7 Response of the system:

a- System response for P-controller:

\[ G_c = K_c = 0.65 \]
\[ G_v = \frac{2}{(0.2s + 1)} \]
\[ G_p = \frac{5}{(2s + 1)(s + 1)} \]
\[ G_m = \frac{1}{(0.1s + 1)} \]

The overall transfer function and system response for P-controller was determined using MATLAB:

\[
M = 0.65; \\
\text{num} = 2; \\
\text{den} = [0.2 \ 1]; \\
W = \text{tf(num,den)}; \\
\text{num1} = 5; \\
\text{den1} = [2 \ 3 \ 1]; \\
R = \text{tf(num1,den1)}; \\
\text{num2} = 1; \\
\text{den2} = [0.1 \ 1]; \\
Z = \text{tf(num2,den2)}; \\
P = \text{feedback(M*W*R,Z)};
\]
\[ 0.65 s + 6.5 \]
\[ P = \frac{0.04 s^4 + 0.66 s^3 + 2.92 s^2 + 3.3 s + 7.5}{0.04 s^4 + 0.66 s^3 + 2.92 s^2 + 3.3 s + 7.5} \]

Continuous-time transfer function.

>> step(P)

![Step Response Graph](image)

**Fig 4.11 System response for P-controller of loop1**

b- System response for PI-controller:
\[ G_c = \frac{K_c}{1 + \frac{1}{\tau_i}} \]
using (Z-N) table for PI-controller \[ K_c = 0.585 \]
\[ \tau_i = 2.3 \]
\[ G_c = \frac{(1.3455s + 0.585)}{2.3s} \]
The overall transfer function and system response for PI-controller was determined by MATLAB:

```matlab
>> num=[1.3455 0.585];
den=[2.3 0];
A=tf(num,den);
num1=2;
den1=[0.2 1];
B=tf(num1,den1);
num2=5;
den2=[2 3 1];
C=tf(num2,den2);
num3=1;
den3=[0.1 1];
D=tf(num3,den3);
E=feedback(A*B*C,D)

1.345 s^2 + 14.04 s + 5.85
E= ---------------------------------------------------------
    0.092 s^5 + 1.518 s^4 + 6.716 s^3 + 7.59 s^2 + 15.75 s + 5.85

Continuous-time transfer function.

>> step(E)
```
c-System response for PID-controller:

\[ G(s) = K_c(1 + \frac{1}{\tau_i s} + \frac{1}{\tau_d s}) \]

using (Z-N)table for PID controller: \( K_c = 0.78 \), \( \tau_i = 1.4 \), \( \tau_d = 0.34 \)

\[ G_c = \frac{(0.371^2 + 1.092s + 0.78)}{1.4s} \]

The overall transfer function and system response for PID-controller were determined using MATLAB:

```matlab
>> num=[0.37128 1.092 0.78];
den=[1.4 0];
A=tf(num,den);
num1=2;
den1=[0.2 1];
B=tf(num1,den1);
num2=5;
```

**Fig 4.12 System response for PI-controller of loop1**
den2=[ 2 3 1];
C=tf(num2,den2);
num3=[0.1 1];
D=tf(num3,den3);
E=feedback(A*B*C,D)

\[0.3713 s^3 + 4.805 s^2 + 11.7 s + 7.8\]

\[E = \frac{0.056 s^5 + 0.924 s^4 + 4.459 s^3 + 9.425 s^2 + 13.1 s + 7.8}{1}\]

Continuous-time transfer function.

>> step(E)

>>
d-System Response for P, PI and PID-controller:

MATLAB format:

num=[0.65 6.5];
den=[0.04 0.66 2.92 3.3 7.5];
sys=tf(num,den);
step(sys)
hold
num=[1.345 14.04 5.85];
den=[0.092 1.518 6.716 7.59 15.75 5.85];
sys=tf(num,den);
step(sys)
num=[0.3713 4.805 11.75 7.8];
den=[0.056 0.924 4.088 8.333 12.32 7.8];
sys=tf(num,den);
step(sys)

Fig 4.14 System response for P, PI&PID-controller of loop1

RED color: PID    Blue color: P     Green color: PI

Table 4.3 Simulation Parameters of loop1

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time Sec.</th>
<th>Overshoot</th>
<th>Decay ratio</th>
<th>Rise time Sec.</th>
<th>Response time sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.01</td>
<td>1.37</td>
<td>0.76</td>
<td>0.712</td>
<td>13.4</td>
</tr>
<tr>
<td>PI</td>
<td>2.19</td>
<td>1.74</td>
<td>0.8</td>
<td>0.735</td>
<td>30.5</td>
</tr>
<tr>
<td>PID</td>
<td>1.58</td>
<td>1.51</td>
<td>0.72</td>
<td>0.577</td>
<td>7.54</td>
</tr>
</tbody>
</table>

4.2.8 Appling the Root – locus using MATLAB (loop2):

OLTTF was taken, use MATLAB to plot Root – locus and obtain the ultimate gain (Ku), ultimate period (Pu), and frequency (w).

OLTTF = 0.1Kc/(0.3s+1)(4s+1)(0.2s+1)
MATLAB format
num=0.1;
den=[0.24 2.06 4.5 1];
sys=tf(num,den);
rlocus(sys)

the results of Root – locus in MATLAB are:
Gain (Ku) =382 , w= 4.36 , Pu=1.44sec.

4.2.9 Bode plot method of loop 2
To determine the ultimate gain(Ku), ultimate period(Pu) using MATLAB:

\[ 0.1Kc/(0.3s+1)(4s+1)(0.2s+1)=0 \]
Matlab format:
num=0.1;
den=[0.24 2.06 4.5 1];
sys=tf(num,den);
bode(sys),grid

Fig 4.16 Bode diagram of loop2

At -180°, \( w_{co} = 4.27 \), \( P_u = 2 \pi / 4.27 = 1.47 \)

Magnitude = -51.3 \( \rightarrow 20 \log A_r = -51.3 \) \( \therefore A_r = 0.0027 \)

\( K_u = 1/0.0027 = 370 \)

Table 4.4 Summary of loop2

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate gain ( K_u )</th>
<th>Ultimate period ( P_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh-Herwitz</td>
<td>365</td>
<td>1.45</td>
</tr>
<tr>
<td>Direct sub.</td>
<td>376</td>
<td>1.45</td>
</tr>
<tr>
<td>Root locus</td>
<td>381</td>
<td>1.44</td>
</tr>
<tr>
<td>Bode plot</td>
<td>370</td>
<td>1.47</td>
</tr>
<tr>
<td>Average</td>
<td>373</td>
<td>1.452</td>
</tr>
</tbody>
</table>
Table 4.5 (Z-N) stability and tuning of average of loop2

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>τi</th>
<th>τd</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>186.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>167.85</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>291</td>
<td>0.725</td>
<td>0.18</td>
</tr>
</tbody>
</table>

4.2.10-Response of the system:

a- System response for P-controller:

Gc=Kc=186.5
Gv=1/(0.3s+1)
Gp=0.1/(4s+1)
Gm=1/(0.2s+1)

The overall transfer function and system response for P-controller was determined using MATLAB:

```matlab
>> M=186.5;
num=1;
den=[0.3 1];
W=tf(num,den);
num1=0.1;
den1=[4 1];
R=tf(num1,den1);
um2=1;
den2=[0.2 1];
Z=tf(num2,den2);
P=feedback(M*W*R,Z)
```
3.73 s + 18.65

\[ P = \frac{0.24 s^3 + 2.06 s^2 + 4.5 s + 19.65}{1} \]

Continuous-time transfer function.

\[ \text{>>Step}(P) \]

\[ \text{Fig 4.17 System response for P-controller of loop2} \]

b - System response for PI-controller:

\[ G_c = K_c(1 + \frac{1}{\tau_i s}) \]

using (Z-N) table for PI-controller

\[ K_c = 167.85 \quad \tau_i = 1.2 \]

\[ G_c = 167.85(1 + \frac{1}{1.2s}) = 201.42s + \frac{167.85}{1.2s} \]

The overall transfer function and system response for PI-controller was determined by MATLAB:

\[ \text{>> num=[201.42 167.85];} \]

\[ \text{den=[1.2 0];} \]

\[ \text{A=tf(num,den);} \]

\[ \text{num1=1;} \]
den1=[0.3 1];
B=tf(num1,den1);
num2=0.1;
den2=[4 1];
C=tf(num2,den2);
num3=1;
den3=[0.2 1];
D=tf(num3,den3);
E=feedback(A*B*C,D)

\[4.028 s^2 + 23.5 s + 16.79\]

E=-------------------------------------------------------------

\[0.288 s^4 + 2.472 s^3 + 5.4 s^2 + 21.34 s + 16.79\]

Continuous-time transfer function.

>> step(E)
c-response for PID-controller:

\[ G(s) = K_c\left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \], using (Z-N)table for PID controller: \( K_c = 291 \), \( \tau_i = 0.725 \), \( \tau_d = 0.18 \)

\[ G_c = \frac{(211 + 291 + 37.9s^2)}{0.725s} \]

The overall transfer function and system response for PID-controller were determined using MATLAB:

```matlab
num=[211 291 37.9];
den=[0.725 0];
A=tf(num,den);
num1=1;
den1=[0.3 1];
B=tf(num1,den1);
num2=0.1;
den2=[4 1];
```
C = tf(num2, den2);
num3 = 1;
den3 = [0.2 1];
D = tf(num3, den3);
E = feedback(A * B * C, D)

\[ 4.22 s^3 + 26.92 s^2 + 29.86 s + 3.79 \]
\[ E = \frac{1.74 s^4 + 1.494 s^3 + 24.36 s^2 + 29.83 s + 3.79}{1} \]
Continuous-time transfer function.

>> Step(E)

Fig 4.19 System response for PID-controller of loop2
d-System Response for P, PI and PID-controller:

MATLAB format:

```matlab
>> num=[3.73 18.65];
den=[0.24 2.06 4.5 19.65];
sys=tf(num,den);
step(sys)
hold
num1=[4.028 23.5 16.79];
den1=[0.288 2.472 5.4 21.34 16.79];
sys=tf(num1,den1);
step(sys)
num2=[4.22 26.92 29.86 3.79];
den2=[0.174 1.494 24.36 29.83 3.79];
sys=tf(num2,den2);
step(sys)
```

Fig 4.20 System response for P, PI & PID-controller of loop2
### Table 4.6 Simulation parameters of loop2

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time (Sec.)</th>
<th>Overshoot</th>
<th>Decay ratio</th>
<th>Rise time (Sec.)</th>
<th>Response time sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.88</td>
<td>1.58</td>
<td>0.74</td>
<td>0.322</td>
<td>6.99</td>
</tr>
<tr>
<td>PI</td>
<td>0.957</td>
<td>1.98</td>
<td>0.81</td>
<td>0.32</td>
<td>19.3</td>
</tr>
<tr>
<td>PID</td>
<td>0.152</td>
<td>2.09</td>
<td>0.53</td>
<td>0.035</td>
<td>&gt;1.5</td>
</tr>
</tbody>
</table>

#### 4.2.11 Applying the Root–locus using MATLAB (loop3):

OLTFT was taken, use MATLAB to plot Root–locus and obtain the ultimate gain (Ku), ultimate period (Pu), and frequency (w).

\[
\text{OLTFT} = \frac{0.2k_c}{(2s+1)(0.5s+1)(3s+1)}
\]

MATLAB format:

```matlab
num=0.2;
den=[3 8.5 5.5 1];
sys=tf(num,den);
rlocus(sys)
```
the results of Root – locus in MATLAB are:

Ku= 72.8 , w=1.35 , Pu= 2Π/1.35= 4.65sec

4.2.12 Bode plot method of loop3

To determine the ultimate gain(Ku), ultimate period(Pu) using MATLAB:

0.2kc/(2s+1)(0.5s+1)(3s+1)=0

MATLAB format:

num=0.2;
den=[3 8.5 5.5 1];
sys=tf(num,den);
bode(sys),grid
At -180°, \( w=1.38 \)  \( Pu= \frac{2\pi}{1.38}= 4.55 \)
Magnitude = -37.6°, 20 log Ar= -37.6°  \( \therefore Ar=0.013 \)
\( Ku=1/0.013= 75.8 \)

**Table 4.7 Summary of loop3**

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate gain Ku</th>
<th>Ultimate period Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh-Herwitz</td>
<td>73.4</td>
<td>4.55</td>
</tr>
<tr>
<td>Direct sub.</td>
<td>72.4</td>
<td>4.56</td>
</tr>
<tr>
<td>Root locus</td>
<td>72.8</td>
<td>4.65</td>
</tr>
<tr>
<td>Bode plot</td>
<td>75.8</td>
<td>4.55</td>
</tr>
<tr>
<td>Average</td>
<td>73.6</td>
<td>4.57</td>
</tr>
</tbody>
</table>
Table 4.8 (Z-N) stability and tuning system of average of loop3

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>τi</th>
<th>τd</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>36.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>33.12</td>
<td>3.8</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>44.16</td>
<td>2.28</td>
<td>0.57</td>
</tr>
</tbody>
</table>

4.2.13 Response of the system:

a- System response for P-controller:

\[ G_c = K_c = 36.8 \]
\[ G_v = \frac{1}{2s+1} \]
\[ G_p = \frac{0.2}{0.5s+1} \]
\[ G_m = \frac{1}{3s+1} \]

The overall transfer function and system response for P-controller was determined using MATLAB:

```matlab
>> M=36.8;
num=1;
den=[2 1];
W=tf(num,den);
num1=0.2;
den1=[0.5 1];
R=tf(num1,den1);
um2=1;
den2=[3 1];
Z=tf(num2,den2);
P=feedback(M*W*R,Z)
```
\[ 22.08 s + 7.36 \]
\[ P = \frac{3 s^3 + 8.5 s^2 + 5.5 s + 8.36}{s} \]

Continuous-time transfer function.

\[ \text{>> step}(P) \]

\[ \text{Fig 4.23} \]

System response for PI-controller of loop3:

\[ G_c = K_c(1+1/\tau_i) \text{ , using (Z-N) table for PI-controller } K_c = 33.12 \; \tau_i = 3.8 \]
\[ G_c = 33.12(1+1/3.8s) \text{ , } G_c = (125.8s+33.12)/3.8s \]

The overall transfer function and system response for PI-controller was determined by MATLAB:
\[
\begin{align*}
\text{num} &= [33.12 \ 125.8] ; \\
den &= [3.8 \ 0] ; \\
A &= \text{tf}(\text{num}, \text{den}) ; \\
\text{num1} &= 1 ; \\
den1 &= [2 \ 1] ; \\
B &= \text{tf}(\text{num1}, \text{den1}) ; \\
\text{num2} &= 0.2 ; \\
den2 &= [0.5 \ 1] ; \\
C &= \text{tf}(\text{num2}, \text{den2}) ; \\
\text{num3} &= 1 ; \\
den3 &= [3 \ 1] ; \\
D &= \text{tf}(\text{num3}, \text{den3}) ; \\
E &= \text{feedback}(A * B * C, D)
\end{align*}
\]

\[
19.87 s^2 + 82.1 s + 25.16
\]

\[
E = \frac{11.4 s^4 + 32.3 s^3 + 20.9 s^2 + 10.42 s + 25.16}{s^4 + 3 s^3 + 3 s^2 + 1 s + 1}
\]

Continuous-time transfer function.

\[
\text{step}(E)
\]
c-response for PID-controller:

\[ G(s) = K_c\left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \]

using (Z-N)table for PID controller: \( K_c = 44.16 \), \( \tau_i = 2.28 \), \( \tau_d = 0.57 \)

\[ G_c = 44.16\left(1 + \frac{1}{2.28 s} + 0.57 s^2\right) = \frac{100.6s + 44.16 + 57.3s^2}{2.28s} \]

The overall transfer function and system response for PID-controller were determined using MATLAB:

```
>> num=[44.16 100.6 57.3];
>> den=[2.28 0];
>> A=tf(num,den);
>> num1=1;
>> den1=[2 1];
```
B=tf(num1,den1);
num2=0.2;
den2=[0.5 1];
C=tf(num2,den2);
num3=1;
den3=[3 1];
D=tf(num3,den3);
E=feedback(A*B*C,D)

\[
26.5 s^3 + 69.19 s^2 + 54.5 s + 11.46
\]
E= -----------------------------------------------
\[
6.84 s^4 + 19.38 s^3 + 21.37 s^2 + 22.4 s + 11.46
\]
Continuous-time transfer function.

>> step(E)
Fig 4.25 System response for PID-controller of loop3

d-System Response for P, PI, PID and PID-controller:
MATLAB format:
num=[22.08 7.36];
den=[3 8.5 5.5 8.36];
sys=tf(num,den);
step(sys)
hold
num=[19.87 82.1 25.16];
den=[11.4 32.3 20.9 10.42 25.16];
sys=tf(num,den);
step(sys)
num=[26.5 69.19 54.5 11.46];
den=[6.84 19.38 21.37 22.4 11.46];
sys=tf(num,den);
step(sys)

![Step Response](image)

Fig 4.26 System response for P, PI&PID-controller of loop3

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time (Sec.)</th>
<th>Overshoot</th>
<th>Decay Ratio</th>
<th>Rise Time (Sec.)</th>
<th>Response time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.06</td>
<td>2.89</td>
<td>0.59</td>
<td>0.421</td>
<td>27.2</td>
</tr>
<tr>
<td>PI</td>
<td>&gt;250</td>
<td>-1.34e+29</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>1.61</td>
<td>3.72</td>
<td>0.6</td>
<td>0.214</td>
<td>40.7</td>
</tr>
</tbody>
</table>

4.2.14 Applying the Root–locus using MATLAB (loop4):

OLTFT was taken, use MATLAB to plot Root–locus and obtain the ultimate gain (Ku), ultimate period (Pu), and frequency (w).
OLT$F= 3k/(0.5s+1)(0.1s+1)(1.5s+1) = 3k/(0.075s^3+1.1s^2+3.7s+2)$

MATLAB format

num=3;
den=[0.075 1.1 3.7 2];
sys=tf(num,den);
rlocus(sys)

the results of Root – locus in MATLAB are:
Gain ($K_u$) =17.3 , $w= 7$, $P_u=2\pi/7 = 0.89$sec.

4.2.15 Bode plot method of loop4 to determine the ultimate gain($K_u$), ultimate period($P_u$) using MATLAB:

num=3;
den=[0.075 1.1 3.7 2];
sys=tf(num,den);
bode(sys),grid
Fig 4.28Bode diagram of loop4

At -180 \( w = 7.09 \) \( \Rightarrow \) \( Pu = \frac{2\pi}{7.09} = 0.88 \) sec.

Magnitude = -25 \( \rightarrow \) 20 log AR = -25

\[ \therefore AR = 0.056 \]

\[ \therefore Ku = \frac{1}{0.056} = 17.7 \]

Table 4.10 Summary of loop4

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate gain Ku</th>
<th>Ultimate Period Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh-Herwitz</td>
<td>17.8</td>
<td>0.89</td>
</tr>
<tr>
<td>Direct sub.</td>
<td>17.4</td>
<td>0.89</td>
</tr>
<tr>
<td>Root locus</td>
<td>17.7</td>
<td>0.88</td>
</tr>
<tr>
<td>Bode plot</td>
<td>17.3</td>
<td>0.89</td>
</tr>
<tr>
<td>Average</td>
<td>17.55</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Table 4.11 (Z-N) stability and tuning system of average of loop4

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>( \tau_l )</th>
<th>( \tau_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>8.77</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>7.89</td>
<td>0.74</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>10.53</td>
<td>0.445</td>
<td>0.11</td>
</tr>
</tbody>
</table>

4.2.16 Response of the system:

a- System response for P-controller:

\[
G_c = K_c = 8.77 \\
G_v = \frac{2}{0.5s + 2} \\
G_p = \frac{1.5}{0.1s + 1} \\
G_m = \frac{1}{1.5s + 1}
\]

The overall transfer function and system response for P-controller was determined using MATLAB:

\[
> \text{M}=8.77; \text{num}=2; \text{den}=[0.5 2]; \text{W}=\text{tf}(\text{num,den}); \text{num1}=1.5; \text{den1}=[0.1 1]; \text{R}=\text{tf}(\text{num1,den1}); \text{num2}=1; \text{den2}=[1.5 1]; \text{Z}=\text{tf}(\text{num2,den2}); \text{P}=\text{feedback}(\text{M*W*R,Z})
\]

\[
39.46 s + 26.31 \\
P = \text{-----------------------------} \\
0.075 s^3 + 1.1 s^2 + 3.7 s + 28.31
\]
Continuous-time transfer function.
Step(P)

Fig 4.29 System response for P-controller of loop4

b-System response for PI-controller:

\[ G_c = K_c (1 + \frac{1}{\tau_i s}) \], using (Z-N) table for PI-controller \( K_c = 7.89 \) \( \tau_i = 0.74 \)
\[ G_c = 7.89 (1 + 1/0.74s) \quad G_c = (5.83s + 7.89)/0.74s \]

The overall transfer function and system response for PI-controller was determined by MATLAB:

\[
\text{>> num} = [7.89 \quad 5.83];
\text{den} = [0.74 \quad 0];
\text{A} = \text{tf(num,den)};
\text{num1} = 2;
\text{den1} = [0.5 \quad 2];
\]
\begin{verbatim}
B=tf(num1,den1);
num2=1.5;
den2=[0.1 1];
C=tf(num2,den2);
num3=1;
den3=[1.5 1];
D=tf(num3,den3);
E=feedback(A*B*C,D)

\[ 35.5 s^2 + 49.91 s + 17.49 \]
E= 0.0555 s^4 + 0.814 s^3 + 2.738 s^2 + 25.15 s + 17.49
Continuous-time transfer function.

>> step(E)
\end{verbatim}

Fig 4.30 System response for PI-controller of loop4
c-response for PID-controller:
\[ G(s) = K_c(1+1/\tau_i s+\tau_d s) \]
using (Z-N)table for PID controller: \( K_c=10.53 \), \( \tau_i=0.445 \), \( \tau_d=0.11 \)
\[ G_c = 10.53(1+1/0.445s +0.11s) = (4.68 + 10.53 + 0.5s^2)/0.445s \]

The overall transfer function and system response for PID-controller were determined using MATLAB:

```matlab
>> num=[4.68 10.53 0.5];
den=[0.445 0];
A=tf(num,den);
num1=2;
den1=[0.5 2];
B=tf(num1,den1);
num2=1.5;
den2=[0.1 1];
C=tf(num2,den2);
num3=1;
den3=[1.5 1];
D=tf(num3,den3);
E=feedback(A*B*C,D)
```

\[ 21.06 s^3 + 61.42 s^2 + 33.84 s + 1.5 \]
\[ E= \frac{0.03338 s^4 + 0.4895 s^3 + 15.69 s^2 + 32.48 s + 1.5}{0.03338 s^4 + 0.4895 s^3 + 15.69 s^2 + 32.48 s + 1.5} \]

Continuous-time transfer function.

```matlab
>> step(E)
```
Fig 4.31 System response for PID-controller of loop 4

d-System Response for P, PI and PID-controller:

MATLAB format:

```matlab
num=[39.46 26.31];
den=[0.075 1.1 3.7];
sys=tf(num,den);
step(sys)
hold
num=[35.5 49.91 17.49];
den=[0.0555 0.814 2.738 25.15 17.49];
sys=tf(num,den);
step(sys)
num=[21.06 61.42 33.84 1.5];
den=[0.03338 0.4895 15.69 32.48 1.5];
```
sys=tf(num,den);
step(sys)

Fig 4.32 System response for P, PI&PID-controller of loop4

Table 4.12 Simulation parameters of loop4

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time (Sec.)</th>
<th>Overshoot</th>
<th>Decay Ratio</th>
<th>Rise time (Sec.)</th>
<th>Response time sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.366</td>
<td>6.37</td>
<td>0.48</td>
<td>0.046</td>
<td>5.22</td>
</tr>
<tr>
<td>PI</td>
<td>0.365</td>
<td>8.25</td>
<td>0.76</td>
<td>0.042</td>
<td>14.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.066</td>
<td>20.8</td>
<td>0.18</td>
<td>0.0013</td>
<td>0.6</td>
</tr>
</tbody>
</table>
4.3 The selection of controller:

4.3.1 Loop1: according to parameters table of loop1, P-controller is the less overshoot so it’s selected for the loop.

Table 4.13 loop1 parameters

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time</th>
<th>Overshoot</th>
<th>Decay ratio</th>
<th>Rise time</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.01</td>
<td>1.37</td>
<td>0.76</td>
<td>0.712</td>
<td>13.4</td>
</tr>
<tr>
<td>PI</td>
<td>2.19</td>
<td>1.74</td>
<td>0.80</td>
<td>0.735</td>
<td>30.5</td>
</tr>
<tr>
<td>PID</td>
<td>1.58</td>
<td>1.51</td>
<td>0.72</td>
<td>0.577</td>
<td>7.54</td>
</tr>
</tbody>
</table>

![Fig 4.33.A Selected controller (P-controller) of loop1](image)

![Fig 4.33.B Control system block diagram selected for loop 1](image)
4.3.2 Loop2: P-controller is the less overshoot so it’s selected for the loop.

Table 4.14 loop2 parameters

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time Sec.</th>
<th>Overshoot</th>
<th>Decay ratio</th>
<th>Rise time Sec.</th>
<th>Response time sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.88</td>
<td>1.58</td>
<td>0.74</td>
<td>0.322</td>
<td>6.99</td>
</tr>
<tr>
<td>PI</td>
<td>0.957</td>
<td>1.98</td>
<td>0.81</td>
<td>0.32</td>
<td>19.3</td>
</tr>
<tr>
<td>PID</td>
<td>0.152</td>
<td>2.09</td>
<td>0.53</td>
<td>0.035</td>
<td>&gt;1.5</td>
</tr>
</tbody>
</table>

Fig 4.34.A Selected controller (P-controller) of loop2

Fig 4.34.B Control system block diagram selected for loop 2
4.3.3 Loop3: P-controller is the less overshoot so it’s selected for the loop.

Table 4.15 loop3 parameters

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time Sec.</th>
<th>Overshoot</th>
<th>Decay Ratio</th>
<th>Rise Time Sec.</th>
<th>Response time sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.06</td>
<td>2.89</td>
<td>0.59</td>
<td>0.421</td>
<td>27.2</td>
</tr>
<tr>
<td>PI</td>
<td>&gt;250</td>
<td>-1.34e+29</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>1.61</td>
<td>3.72</td>
<td>0.6</td>
<td>0.214</td>
<td>40.7</td>
</tr>
</tbody>
</table>

Fig 4.35.A Selected controller (P-controller) of loop3

Fig 4.35.B Control system block diagram selected for loop3
4.3.4 Loop4: P-controller is the less overshoot so it’s selected for the loop.

Table 4.16 loop4 parameters

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Beak time Sec.</th>
<th>Overshoot</th>
<th>Decay Ratio</th>
<th>Rise time Sec.</th>
<th>Response time sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.366</td>
<td>6.37</td>
<td>0.48</td>
<td>0.046</td>
<td>5.22</td>
</tr>
<tr>
<td>PI</td>
<td>0.365</td>
<td>8.25</td>
<td>0.76</td>
<td>0.042</td>
<td>14.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.066</td>
<td>20.8</td>
<td>0.18</td>
<td>0.0013</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fig 4.36.A Selected controller (P-controller) of loop4

Fig 4.36.B Control system block diagram selected for loop 4
4.4 Air cooler section:

![Diagram of Air cooler section]

Fig 4.37 Air cooler physical diagram

4.4.1 Loop air analysis:

Transfer functions: \( G_c = K_c \), \( G_v = \frac{4}{1.2s+1} \), \( G_p = \frac{1}{3s+0.5} \), \( G_m = \frac{2}{1.5s+2} \)

![Diagram of loop air block diagram]

Fig 4.38 loop air block diagram

4.4.1.A-System stability:

\[
OLTF = \frac{8kc/(1.2s+1)(3s+0.5)(1.5s+2)}{8kc/(5.4s^3+12.6s^2+7.95s+1)} = \frac{5.4s^3+12.6s^2+7.95s+1}{5.4s^3+12.6s^2+7.95s+1+Kc} = 0
\]
\[ \text{charac. Eq: } 5.4s^3 + 12.6s^2 + 7.95s + 1 + 8kc = 0 \]

**Routh-Array Method:**

<table>
<thead>
<tr>
<th>(5.4)</th>
<th>(7.95)</th>
<th>(0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(12.6)</td>
<td>(1+8kc)</td>
<td>(0)</td>
</tr>
<tr>
<td>(b_1)</td>
<td>(c_1)</td>
<td>(b_2=1+8kc)</td>
</tr>
<tr>
<td>(b_2)</td>
<td>(c_2)</td>
<td>(\text{system is stable.})</td>
</tr>
</tbody>
</table>

\[ b_1 = 7.53 - 3.42kc, \Rightarrow kc = 2.2 \]

**Direct sub. Method:**

\[ 5.4s^3 + 12.6s^2 + 7.95s + 1 + 8kc = 0 \]
\[ s = (iw), \quad i^2 = -1 \]
\[ -5.4iw^3 - 12.6w^2 + 7.95iw + 1 + 8kc = 0 \]

Imag. Part: \(-5.4iw^3 + 7.95iw = 0\) \quad \Rightarrow \text{w = 1.2 rad/sec, Pu = } 2\pi/1.2 = 5.2\text{ sec} \]

Real part: \(-12.6w^2 + 1 + 8kc\) \quad w^2 = 1.47 \Rightarrow -12.6*1.47 + 1 + 8kc = 0 \]
\[ \Rightarrow kc = 2.19 \]

4.4.1-B Applying the Root – locus using MATLAB (loop air):

OLT\(F\) was taken, use MATLAB to plot Root – locus and obtain the ultimate gain (K\(u\)), ultimate period (P\(u\)), and frequency (w).

\[ \text{OLT}\(F\) = \frac{8kc}{(5.4s^3 + 12.6s^2 + 7.95s + 1)} \]

Matlab format:

```
num=8;
den=[5.4 12.6 7.95 1];
sys=tf(num,den);
```
the results of Root – locus in MATLAB are:
Gain (Ku) =2.19  ,   w= 1.21  , Pu=5.2sec.

4.4.1-C Bode plot method of loop air
To determine the ultimate gain(Ku), ultimate period(Pu) using MATLAB:
8kc/(5.4s^3+12.6s^2+7.95s+1)
num=8;
den=[5.4 12.6 7.95 1];
sys=tf(num,den);
At $-180^\circ$, $w=1.21$, $Pu=\frac{2\pi}{1.21}=5.2$

Magnitude $=-6.86$, $20\log Ar=-6.86 \therefore Ar=0.45$

Ku=2.2

**Table 4.17 Summary of loop air**

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate gain Ku</th>
<th>Ultimate period Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-H</td>
<td>2.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Direct. Sub</td>
<td>2.19</td>
<td>5.2</td>
</tr>
<tr>
<td>Root locus</td>
<td>2.19</td>
<td>5.2</td>
</tr>
<tr>
<td>Bode plot</td>
<td>2.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Average</td>
<td>2.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Table 4.18 (Z-N) stability and tuning system of average of loop air

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Kc</th>
<th>$\tau_i$</th>
<th>$\tau_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>1.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.99</td>
<td>4.3</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>1.32</td>
<td>2.6</td>
<td>0.65</td>
</tr>
</tbody>
</table>

4.4.2 Response of the system:

a- System response for P-controller:

$G_c=K_c=1.1$

$G_v=4/(1.2s+1)$

$G_p=1/(3s+0.5)$

$G_m=2/(1.5s+2)$

The overall transfer function and system response for P-controller was determined using MATLAB:

```matlab
>> M=1.1;
num=4;
den=[1.2 1];
W=tf(num,den);
num1=1;
den1=[3 0.5];
R=tf(num1,den1);
num2=2;
den2=[1.5 2];
Z=tf(num2,den2);
P=feedback(M*W*R,Z)
```
\[ 6.6 s + 8.8 \]
\[ P= \----------------------------- \]
\[ 5.4 s^3 + 12.6 s^2 + 7.95 s + 9.8 \]

Continuous-time transfer function.

\[ >> \text{step}(P) \]

Fig 4.41 System response for P-controller of loop air

b-System response for PI-controller:

\[ G_c=K_c(1+1/\tau_i) \text{, using (Z-N) table for PI-controller } K_c= 0.99 \quad \tau_i=4.3 \]
\[ G_c=0.99(1+1/4.3s) \text{, } G_c=(4.25s+0.99)/4.3s \]

The overall transfer function and system response for PI-controller was determined by MATLAB:
>> num=[4.25 0.99];
den=[4.3 0];
A=tf(num,den);
num1=4;
den1=[1.2 1];
B=tf(num1,den1);
num2=1;
den2=[3 0.5];
C=tf(num2,den2);
num3=2;
den3=[1.5 2];
D=tf(num3,den3);
E=feedback(A*B*C,D)

\[ 25.5 s^2 + 39.94 s + 7.92 \]

\[ E= \frac{23.22 s^4 + 54.18 s^3 + 34.18 s^2 + 38.3 s + 7.92}{ } \]

Continuous-time transfer function.
>> step(E)

Fig 4.42 System response for PI-controller of loop air

c-response for PID-controller:
\[ G(s) = K_c(1 + \tau_i s + \tau_d) \]
using (Z-N)table for PID controller: 
\[ K_c = 1.32, \ \tau_i = 2.6, \ \tau_d = 0.65 \]
\[ G_c = 1.32(1 + \frac{1}{2.6s} + 0.65) = \frac{3.43s + 1.32 + 2.23s^2}{2.6s} \]

The overall transfer function and system response for PID-controller were determined using MATLAB:
\[ >> \ \text{num}=[3.43 \ 1.32 \ 2.23]; \]
\[ \text{den}=[2.6 \ 0]; \]
\[ A=\text{tf(num,den)}; \]
\[ \text{num1}=4; \]
\[ \text{den1}=[1.2 \ 1]; \]
\[ B=\text{tf(num1,den1)}; \]
\[ \text{num2}=1; \]
\[ \text{den2}=[3 \ 0.5]; \]
C=tf(num2,den2);
num3=2;
den3=[1.5 2];
D=tf(num3,den3);
E=feedback(A*B*C,D)

\[ 20.58 s^3 + 35.36 s^2 + 23.94 s + 17.84 \]
\[ E= \frac{14.04 s^4 + 32.76 s^3 + 48.11 s^2 + 13.16 s + 17.84}{1} \]

Continuous-time transfer function.

>> step(E)

Fig 4.43 System response for PID-controller of loop air
d-System Response for P, PI and PID controller:

MATLAB format:
num=[6.6 8.8];
den=[5.4 12.6 7.95 9.8];
sys=tf(num,den);
step(sys)
hold
num=[25.5 39.94 7.92];
den=[23.22 54.18 34.18 38.3 7.92];
sys=tf(num,den);
step(sys)
num=[20.58 35.36 23.94 17.84];
den=[14.04 32.76 48.11 13.16 17.84];
sys=tf(num,den);
step(sys)
Table 4.19 Simulation parameters of loop air

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Beak time sec</th>
<th>Overshoot</th>
<th>Decay ratio</th>
<th>Rise time</th>
<th>Response time sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>3.22</td>
<td>1.52</td>
<td>0.74</td>
<td>1.11</td>
<td>27.4</td>
</tr>
<tr>
<td>PI</td>
<td>3.33</td>
<td>1.9</td>
<td>0.82</td>
<td>1.15</td>
<td>63.3</td>
</tr>
<tr>
<td>PID</td>
<td>9e+03</td>
<td>9.6e+26</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4.5 Discussion:

The feeding of LPG, heating and vaporizing inside distillation column, cooling, condensing and collecting of overhead product is controlled. The control system are designed and configured in continuous and discrete forms. The process transfer functions are identified from previous studies, in each case the control systems is investigated for stability using (Routh test),(root locus)and (bode method) the control systems are tuned by each method and the adjustable parameters (Kc,τI,τD) are obtained using Ziegler-Nichols technique. In each case the data are plotted on Argand diagram and analyzed for stability. It’s observed the three methods are within very good agreement and it is concluded that any method of the three can be used for stability analysis and tuning. The most appropriate type of controller to the 4 loops was P-controller due to small overshoot compared to PI and PID controllers.
Chapter Five
Conclusions and Recommendations

5.1 Conclusions:

- Heat exchanger situation and pressure of reflux drums are both controlled.
- Stability analysis and tuning through Ziegler-Nichols give adjustable parameters of almost equal magnitude in each case.
- The methods for stability analysis and tuning can confidently be used no matter which method to apply.
- Due to small overshoot values; P-controller has chosen as controller type of loops.

5.2 Recommendations:

1. For further extension studies for unit cooling systems Bode plot, Root-Locus and Rout-Hewritz methods are reliable for control systems stability analysis, therefore they are recommended to be applied.
2. Controlling of Air cooler situation has to change from analog to digital or SCADA system to perform adjusting as rapidly, as accurately and economically as far as possible.
References


