IMPLEMENTATION OF CASCADE CONTROL USING A PROGRAMMABLE LOGIC CONTROLLER

By

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

A. Jay Narain

Avishkar Jay Narain

ABSTRACT

The aim of the project is to implement cascade control using a Programmable Logic Controller (PLC). The PLC module has been successfully used for ON/OFF control in sequential processes. However in this project the PLC has to be configured to accept and monitor a variable input and to supply a variable output (4mA to 20mA) signal in-order to control a final element (e.g. control valve). The significance of this project is to make a comparison between a PLC and a distributed control system (DCS) in terms of controllability and system simplicity. The project requires familiarization in the field of plant process control and instrumentation since it involves the design and implementation of a cascade loop. The cascade controller has been designed to control the level of a liquid in a distillation tower. Familiarization with the PLC hardware and software is another important aspect of the project and took up the bulk of the project time. The final result of the project shows that the PLC is a versatile controller that is able to perform PID control effectively with a relatively simple system. The PLC PID control system is flexible therefore it can be configured to implement any type of control loop e.g. Cascade control.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Cascade Control has been implemented in many Plant Process Control applications. This type of control is usually implemented using a distributed control system (DCS) or a field bus system, which are both complex and expensive to implement and maintain. Cascade control can improve control system performance over single-loop control whenever either:

- Disturbances affect a measurable intermediate or secondary process output that directly affects the primary process output that we wish to control
- The gain of the secondary process, including the actuator, is nonlinear.

In the first case, a cascade control system can limit the effect of the disturbances entering the secondary variable on the primary output [4]. In the second case, a cascade control system can limit the effect of actuator or secondary process gain variations on the control system performance [4]. This type of control therefore increases control over specific processes, which means a better refining of chemicals in the plant. The problem is that on a small scale it is not economical to implement Cascade control using a complex DCS or field bus control system. This type of control can be implemented with PLC control, which is simpler and more economical to implement.

1.2 Problem Statement

1.2.1 Problem Identification

The aim of this project is to utilize the OMRON PLC analogue module to monitor and control a process loop connected in cascade arrangement. The process loop consists of loose field instrumentation (e.g. SMART Transmitters, Control Valves). The project simulates cascade level control of a typical distillation tower (refer to figure 2.3) in a refinery. This type of cascade control is described in detail in section 2.2 of this report.

In a typical control system a variable analogue signal (4mA to 20mA) is used to indicate the value of the process variable and to manipulate the final element after control has taken place. The PLC module is usually used for ON/OFF or BINARY control therefore the biggest challenge to overcome in this project is to configure the OMRON PLC to accept a variable input and to output a variable 4mA to 20mA signal so that it can control the final element (e.g. control valve).

1.2.2 Significance of Project

Cascade Control is usually implemented in a refinery using distributed or field bus control systems, which are complicated and expensive. The PLC system is a reliable, simpler and inexpensive system therefore more economical to use in small-scale plants.

1.2.2.1 Comparison between PLC and DCS systems

The programmable logic controller (PLC) is generally used in machine control while the distributed control system (DCS) dominates process control applications [7]. With technology today the two systems can be used in either of the two applications, since the functional lines between them do not differ entirely [7].

Table 1.1: comparison of DCS and PLC functionality [7]

	DCS functionality	PLC functionality
1.	Able to performed hundreds of analog measurements and control a number of analog outputs	The PLC is fast and most can run an input-compute-output cycle in milliseconds
2.	Has a centralized configuration from which the operator in the control room can monitor and make changes to the control system.	The PLC is fast and most can run an input-compute-output cycle in milliseconds
3.	Requires an operator interface and a complex communications network, so it can send alarms, messages, and trend updates	A PLC can run in a stand-alone configuration there is no need for a complex network
4.	Use operating systems that allow multi-tasking (i.e. download, run applications and perform real-time control functions).	The PLC is a simple, rugged computer that has minimal peripherals and simple operating systems, this increases their reliability

An important difference between the DCS and PLC is how vendors market them. DCS vendors typically sell a complete working, integrated system, which is fully tested, and tailor made for the client [7]. They offer services such as training, installation, field service, and integration with existing Information Technology (IT) systems. A DCS vendor provides a server, a LAN with PCs for office automation, networking support and integration of other applications and systems [7]. The PLC however is usually sold as a single device therefore it is more of a self-implemented system since it is usually simpler to setup and execute [7].

1.3 OBJECTIVE AND SCOPE OF STUDY

1.3.1 THE RELEVANCY OF PROJECT

The project requires to a certain extent, knowledge in plant process control and instrumentation since it involves the design and implementation of a cascade loop, which consists of loose instrumentation. The purpose of the cascade loop is to control the level of the liquid in a distillation tower. Cascade control is a fundamental control configuration used in varied applications in Refineries. Therefore implementing this type of control using a simpler system and added controllability will be relevant in future control systems.

1.3.2 FEASIBILITY OF PROJECT WITHIN SCOPE AND TIME FRAME

The project is anticipated to be feasible within the scope and time frame available. The necessary controller modules and the instruments needed to implement the control system are available. The main obstacle of the project could be if the PLC module is not able to input and output variable signals, however this may be over come by using external circuitry to fulfill this requirement.

The project requires the familiarization of equipment and software, the implementation of the hardware and software aspects of the cascade control system, and performing several "what-ifs" to simulate several situations in the plant environment.

CHAPTER 2

LITERATURE REVIEW

2.1 AUTOMATIC PROCESS CONTROL

Automatic process control is defined as a system in which, without human intervention, the value of a process variable is compared with a given value (set-point) and correction action is taken whenever these two values differ [4]. Before automatic control was developed process control was done manually. Operators were responsible for keeping the process stable by adjusting the process variables (e.g. temperature, pressure etc.). Using manual control meant that process control was inaccurate and unsafe. Automatic process control has lowered labor costs, virtually eliminated human errors, improved process quality and provided greater safety in operation [4]. One of the configurations used in automatic process control is referred to as cascade control, which is described below.

2.2 CASCADE CONTROL

Cascade control requires the output of one controller to act as the set point for the second controller [8]. In this form of control each controller has its own measured variable with only the primary controller having an independent set point and only the secondary controller providing an output to the process [8]. This type of control is needed in situations where a long time lag exists between the manipulated variable (e.g. flow of the process fluid) and its effect on the measured variable (e.g. level of the process fluid) [8].

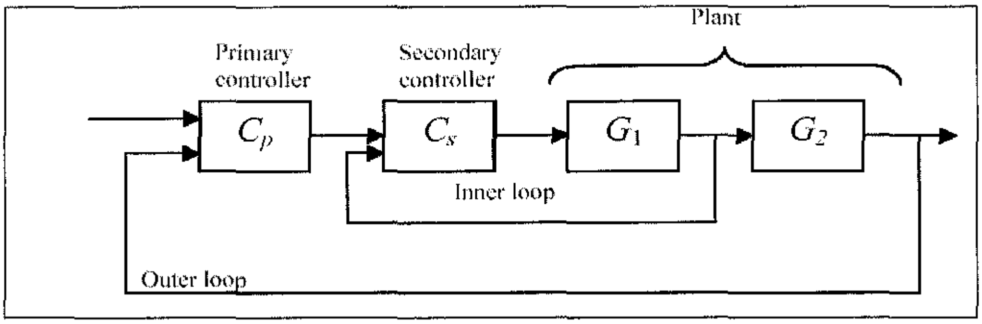


Figure 2.1: Block Diagram representing Cascade Control [8]

2.2.1 Ziegler-Nichols Tuning Method

The Ziegler-Nichols tuning method uses a procedure, which involves measuring the response of a system to a change in set point and then performing calculations to determine the values of P, I and D [5]. This tuning method results in an overshoot response, which stabilizes. The advantage of Ziegler-Nichols tuning is that all three tuning constants k_p, T_d and T_i can be calculated therefore no trial and error is needed to achieve initial tuning [5]. There are two methods to calculate the PID parameters using Ziegler-Nichols method.

2.2.1.1 Oscillation Method

This method requires the system to be a closed loop. Two parameters ultimate gain k_u and ultimate period T_u have to be determined in-order to calculate k_p, T_d and T_i. At the beginning all PID parameters should be set to zero, then the value of kp should be increased to the minimum value that will cause the system to oscillate [5]. The oscillation should be a sustained oscillation. When there is a sustained oscillation the value of k_p used is the ultimate gain of the controller k_u [5].

$$\mathbf{k_p = k_u}$$

The period of the oscillation is the ultimate period of the controller T_u [5]. Once the k_u and T_u are values are found the controller parameters can be calculated using the following formulae:

Proportional Gain ⟶ $\mathbf{k_p = 0.6\ k_u}$

Integral Time ⟶ $\mathbf{T_i = 0.5\ T_u}$

Derivative Time ⟶ $\mathbf{T_d = 0.125\ T_u}$

2.2.1.2 Open Loop Method

This method requires one to determine the dead time (Θ), rise time (τ) and process gain (k_c), these parameters will be used to calculate the PID parameters [5]. The system should be in open-loop unity gain configuration i.e. there should be no feed back loop, k_d should be one and T_i and T_d should not be used. When the system is setup properly a known step change should be applied to the system. When this step change is applied the graph of the process variable PV should be recorded with respect to time [5]. From the graph one can calculate the dead time, rise time and gain of the process. Once these parameters are calculated the values of k_p, T_i and T_d can be calculated using the following formulae [5]:

$$\mathbf{k_p = 1.5\ \tau / (k_d \Theta)}$$

$$\mathbf{T_i = 2.5\ \Theta}$$

$$\mathbf{T_d = 0.4\ \Theta}$$

These values will provide an initial stable system, which may need fine tuning depending on the requirements of the process system being controlled.

2.2.2 Cascade Design Criteria

When designing and implementing a cascade control system there are certain design criteria that need to be considered. These criteria ensure that cascade control is designed properly and used where appropriate. Cascade control should only be used when single loop control does not provide efficient control [4]. Before designing a cascade control system the designer must ensure that there is an acceptable measured secondary variable that is available to be used in the system [6]. The secondary variable has to satisfy three criteria, which are listed below:

- It must indicate the occurrence of an important disturbance.
- The secondary variable must be influenced by the manipulated variable i.e. a causal relationship must exist between the variables.
- The dynamics between the final element and the secondary must be much faster than the dynamics between the secondary variable and the primary variable [4].

These criteria ensure that the secondary loop will have a significant effect on the controlled variable, which will occur whenever an important disturbance occurs [4]. The differences in dynamics ensure that a disturbance is attenuated before it affects the primary variable.

2.2.3 Cascade Performance

The primary objective in cascade control is to divide an otherwise difficult to control process into two portions, whereby a secondary control loop is formed around a major disturbances thus leaving only minor disturbances to be controlled by the primary controller [4].

There are several advantages gained by using cascade control these are listed below [4]:

- Better control of the primary variable
- Primary variable less affected by disturbances
- Faster recovery from disturbances
- Reduce the effective magnitude of a time-lag
- Improve dynamic performance

2.2.4 Applications Of Cascade Control

2.2.4.1 Heat Exchanger

In a heat exchanger a steam flow may heat the product even after the flow has been reduced therefore it will be difficult to achieve the set point temperature[9]. Cascade control is used in the control of a heat exchanger (Figure 2.2). In this application two loops exist which are described below [9]:

- **The Primary Loop:** consists of the primary temperature controller, which receives a signal from a (PV) temperature transmitter that measures the temperature at the outlet of the heat exchanger. The output of the primary controller is connected to the input of the secondary flow controller [9].

- **The Secondary Loop:** The Secondary controller is a flow controller, which receives a signal from a (PV) flow transmitter that measures the steam flow rate into the exchanger. The output of the flow controller is connected to a control valve that directly controls the flow rate of the steam into the heat exchanger [9].

The secondary loop ensures that the steam flow variations are corrected immediately before the hot-water temperature is affected. Since the output of the Primary controller is the set point of the secondary controller temperature set point variations at the output will be corrected [9].

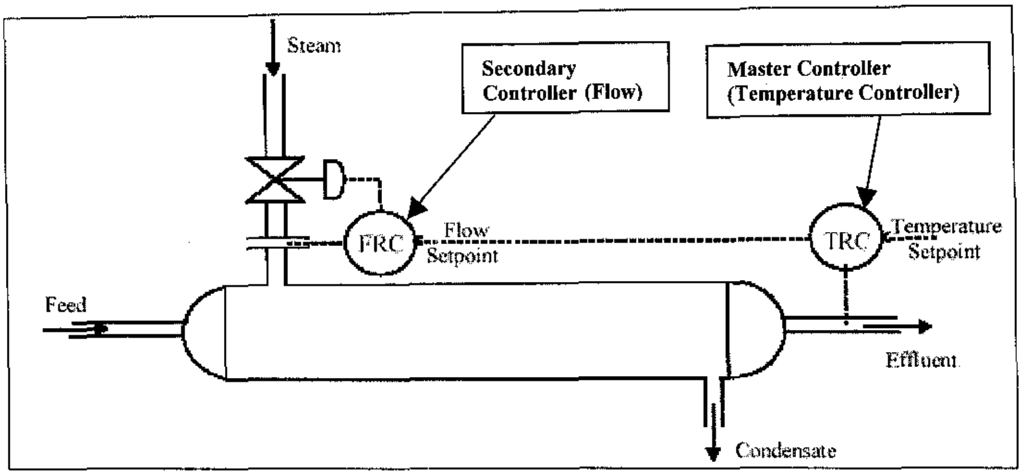


Figure 2.2 Cascade control of effluent temperature via steam flow control [9]

2.2.4.2 Distillation Tower

Another application where Cascade Control is implemented is level control of a drum or in this case (Figure 2.3) a distillation tower [1]. In this instance cascade control is used so that sudden variations in the process fluids level do not have an immediate effect on the flow of the process fluid out of the distillation tower therefore the flow of the process fluid is not erratic [1]. This is important since in most chemical processes the flow rate is required to be constant. In figure 2.3 below cascade control is used to control the level of the process fluid and the flow rate out of the distillation tower. In the diagram below (figure 2.3) the level control loop acts as the *master* controller (primary loop) and the flow control loop acts as the *slave* controller (secondary loop) [1]. The level transmitter feeds signal to level controller (LIC), and the output from the level controller is used as the set point for the flow controller (FIC). The output from the flow controller is used to control the opening of valve (FV), which regulates the flow rate of process fluid from the distillation tower. Value from level and flow loop tuning is used in cascade control to ensure the output of the controller was tuned by gradually adjusting the manipulated variable so that the level of the tank matches the set point [1].

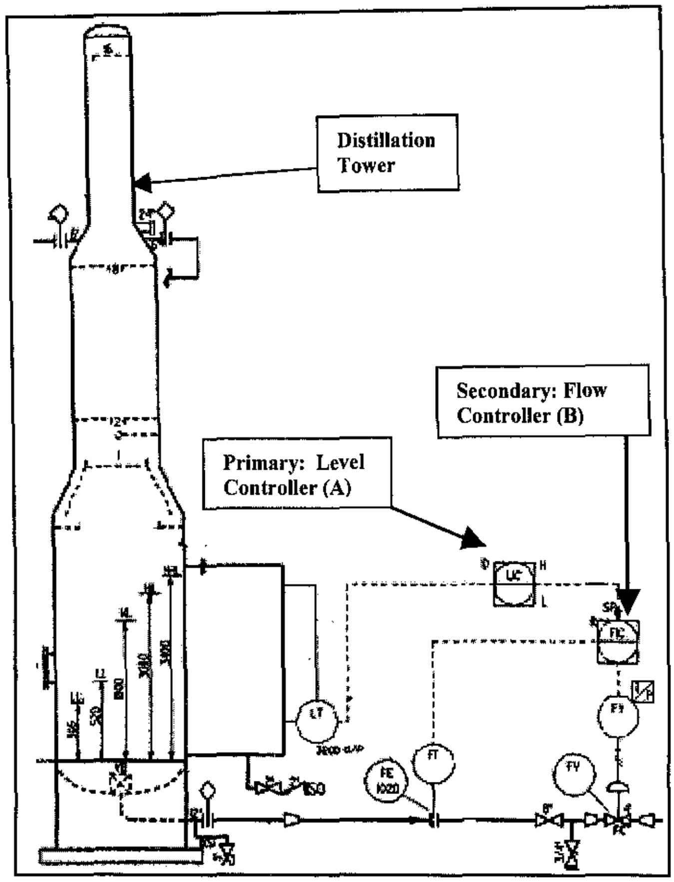


Figure 2.3: Example of cascade control controlling the level of process fluid in a distillation tower

2.3 Proportional – Integral – Derivative (PID) Control

2.3.1 PID Cascade Control

2.3.1.1 The Controller

The critical inputs to a continuous process controller are the process variable (PV) and the set point (SP). During operation, a controller measures the PV, which is the actual value of the variable (e.g. temperature) at any given time, and compares it to the SP, which is the desired value [4]. It then makes the adjustments needed to reduce the error between the two until the process is under proper control. When PV = SP, the error is zero and the process is balanced [4]. To do this, the controller generates an output signal and sends it to the final control element. The controller is able to operate in 3 basic modes or combination of these modes in order to correct the offset between the PV and the SP [4]. These modes are described below in more detail:

2.3.1.2 Proportional Mode (P)

A controller operating in the proportional mode produces a given change in the output for each unit of difference between the PV and SP. In this action there is a linear relation between the value of the actual measurement and the valve position i.e. it is the action that gives a valve movement proportional to the pen movement relative to the set point [4].

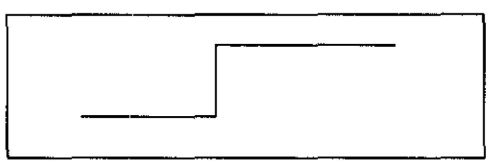


Figure 2.4: Proportional Action (Step Change)

%Proportional Band (PB)

Is the percentage of full scale reading through which the actual measurement must change to produce full stroke travel of the control valve. The wider the percentage PB the slower the controller reacts to changes in the PV. Therefore a wide percentage PB means that the controller has a small gain value. As the percentage PB is narrowed the reaction of the controller becomes faster. At 0% PB a controller operates as an ON/OFF controller [4].

GAIN=100÷PB

2.3.1.3 Integral Mode (I)

This mode eliminates the offset between the set point and the actual value. As long as there is any difference between PV and SP the integral mode or reset acts to adjust the controller output continuously until the offset is reduced to zero.

Controllers often label the reset setting as integral time instead of reset. It is the same adjustment expressed in repeats per minute, while integral time is expressed in minutes per repeat, the inverse of reset [4].

RESET = 1÷ Integral Time
(repeats per min)

INTERGRAL TIME = 1 ÷ Reset
(min per repeat)

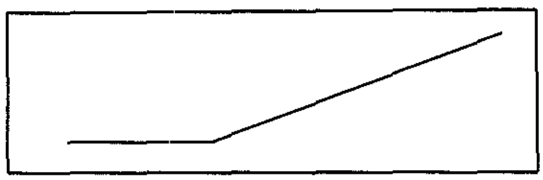


Figure 2.5: Integral Action

2.3.1.4 Derivative Mode (Rate) (D)

The derivative mode or rate action provides additional controller output whenever the process error is changing. The rate of change of the error determines the amount of extra output supplied by the derivative, or rate action. The faster the PV changes relative to the SP, the more output is supplied by the controller. Rate time is expressed in minutes. The rate mode causes a quick response to a quick change and almost no response to a slow change [4].

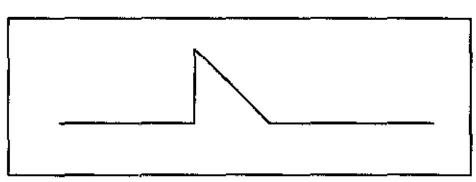


Figure 2.6: Derivative Action

2.3.1.5 Two Mode Control

Proportional + Integral Mode (PI) mode is used when SP and PV change often. It is used to eliminate Offset.

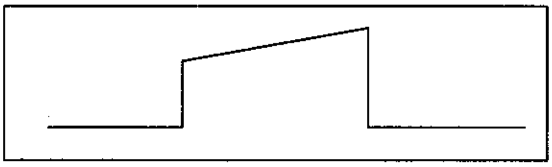


Figure 2.7: PI Control

Proportional + Derivative Control (PD) mode is used when large sudden changes in SP, PV or load occur. This mode corrects rapidly changing errors and minimizes overshoot.

2.3.1.6 Three Mode Control

In this mode Proportional + Integral + Derivative Control (PID) are used. This mode is used where large, sudden changes in PV, SP or load occur. This mode corrects rapidly changing errors, eliminates offset and minimizes overshoot.

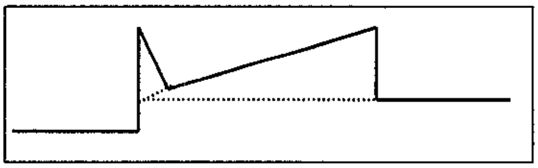


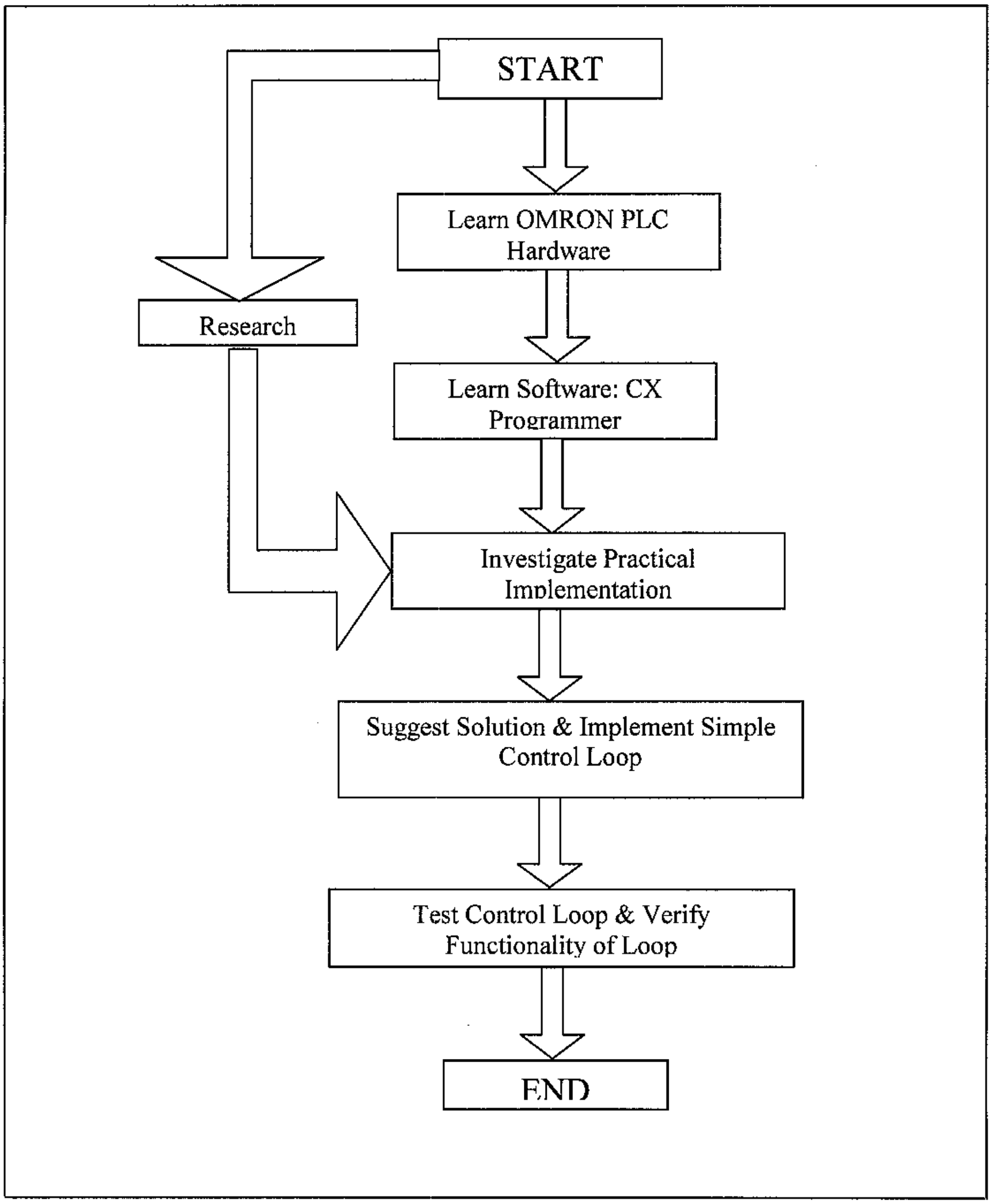
Figure 2.8: PID Control

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 PROCEDURE IDENTIFICATION

In order to successfully execute this project an effective procedure has been identified and followed. This procedure as outlined in the flow chart has emanated from this study.



3.2 TOOLS REQUIRED

There are several tools that are essential to the completion these include:

- **OMRON PLC:** The OMRON PLC is a programmable logic controller, which will be programmed to implement cascade control.
- **CX Programming Software:** This is the software used to program the PLC. The software uses ladder logic to display the logic program.
- **Control Valves:** Is the final element instrument which will be manipulated by the secondary controller i.e. it will control the flow out of the distillation tower.
- **Controllers:** This piece of equipment will be used implement PID and store the set points of the process variables being controlled.

3.3 TIMING DIAGRAM – INITIAL TASK

The diagram below (figure 3.1) shows the actual cascade control system that this project will be modeled on.

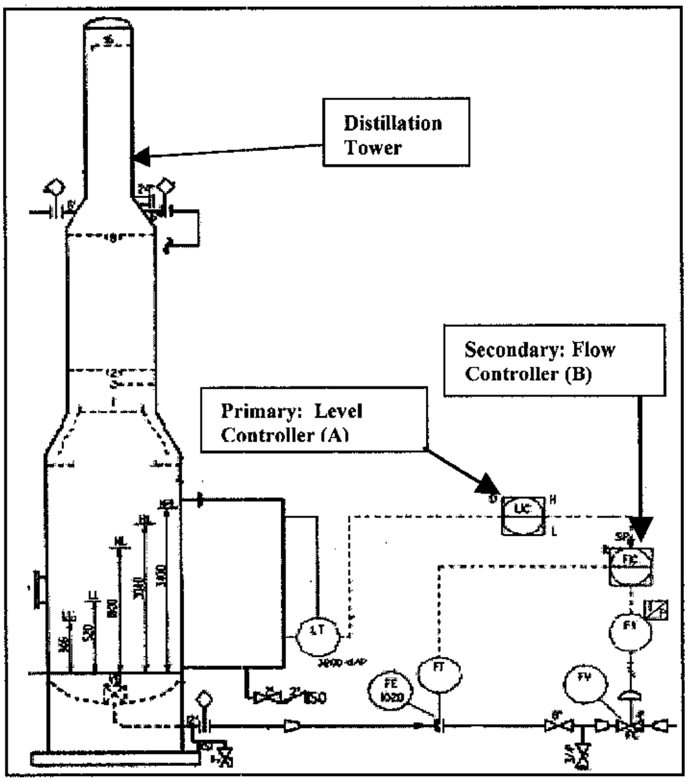


Figure 3.1: Project configuration (level control of a distillation tower)

As one can see the cascade control system is controlling the level of the process fluid in the distillation tower by regulating the flow rate of the liquid out of the tower. The steps of control are identified below:

- The level transmitter (LT) is the INPUT for the primary controller (controller A).
- Controller A OUTPUT determines the SET–POINT (SP) for the secondary controller (controller B).
- The flow transmitter (FT) is the INPUT for controller B.
- The OUTPUT of controller B controls the flow valve (FV) i.e. this valve can either increase or decrease the flow rate out of the Tower.

The timing diagram represents two situations namely:

- Level measurement is **above** SP (i.e. LT has a positive pulse)
- Level measurement is **below** SP (i.e. LT has a negative pulse)

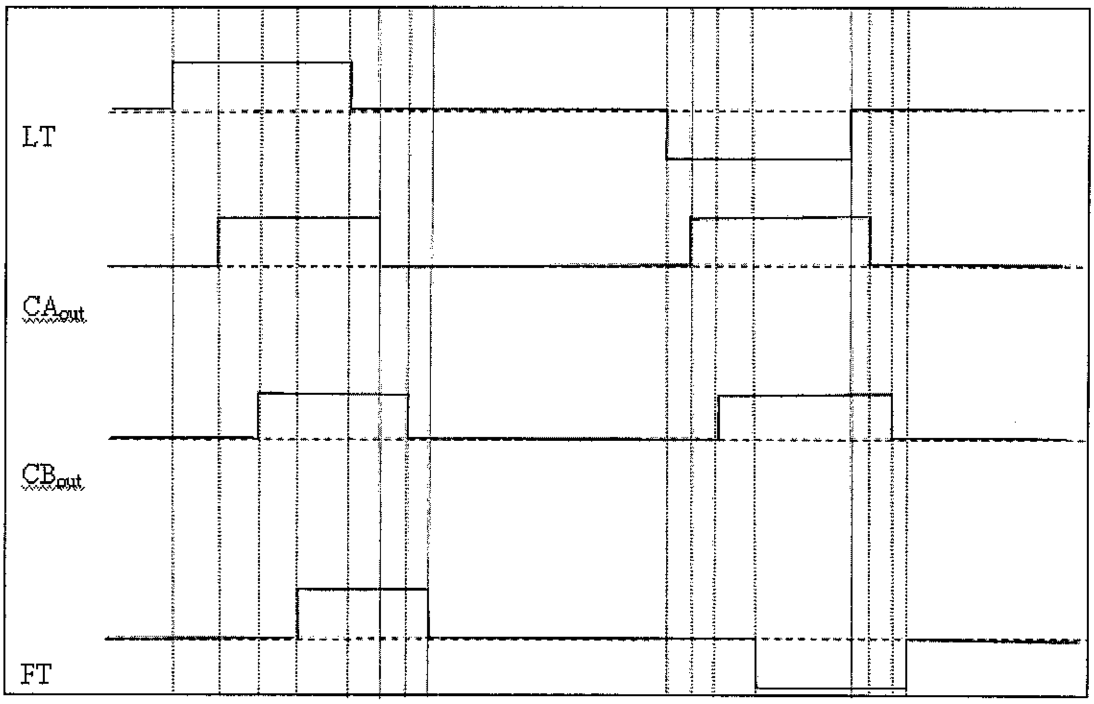


Figure 3.2: Simple Binary Timing Diagram of Cascade Control

The two controllers each have a SP input, a measured variable input (MV) and a controlled output signal:

- Controller A
  - Set-point is specified manually and does not change
  - MV input signal is received from the Level transmitter LT
  - Output signal sets the set-point of controller B
- Controller B
  - SP is determined by Controller A output signal
  - MV input is received from the Flow Transmitter
  - Output signal controls the Flow Valve

3.3.1 Ladder Program Of A Simple Binary System

3.3.1.1 Methodology

In order to the get an optimized ladder diagram (program) one must follow 3 basic steps these are listed below:

I. Create a detailed Timing Diagram which includes all the components that effect the outputs in the application namely:

- Internal Outputs (Holding Relays)
- Switches
- Timers (internal timers)

In reality this is the crucial step that involves careful study of the sequences and to establish the objective of the control.

II. Develop a logical equation of each component of the timing diagram e.g. Timer 1. The general equation is shown below:

$$\textbf{Output} = (\textbf{set} + \textbf{latch}) \cdot \overline{\textbf{reset}}$$

III. Using the equations in step 2 construct a ladder diagram.

3.3.1.2 Timing Diagram

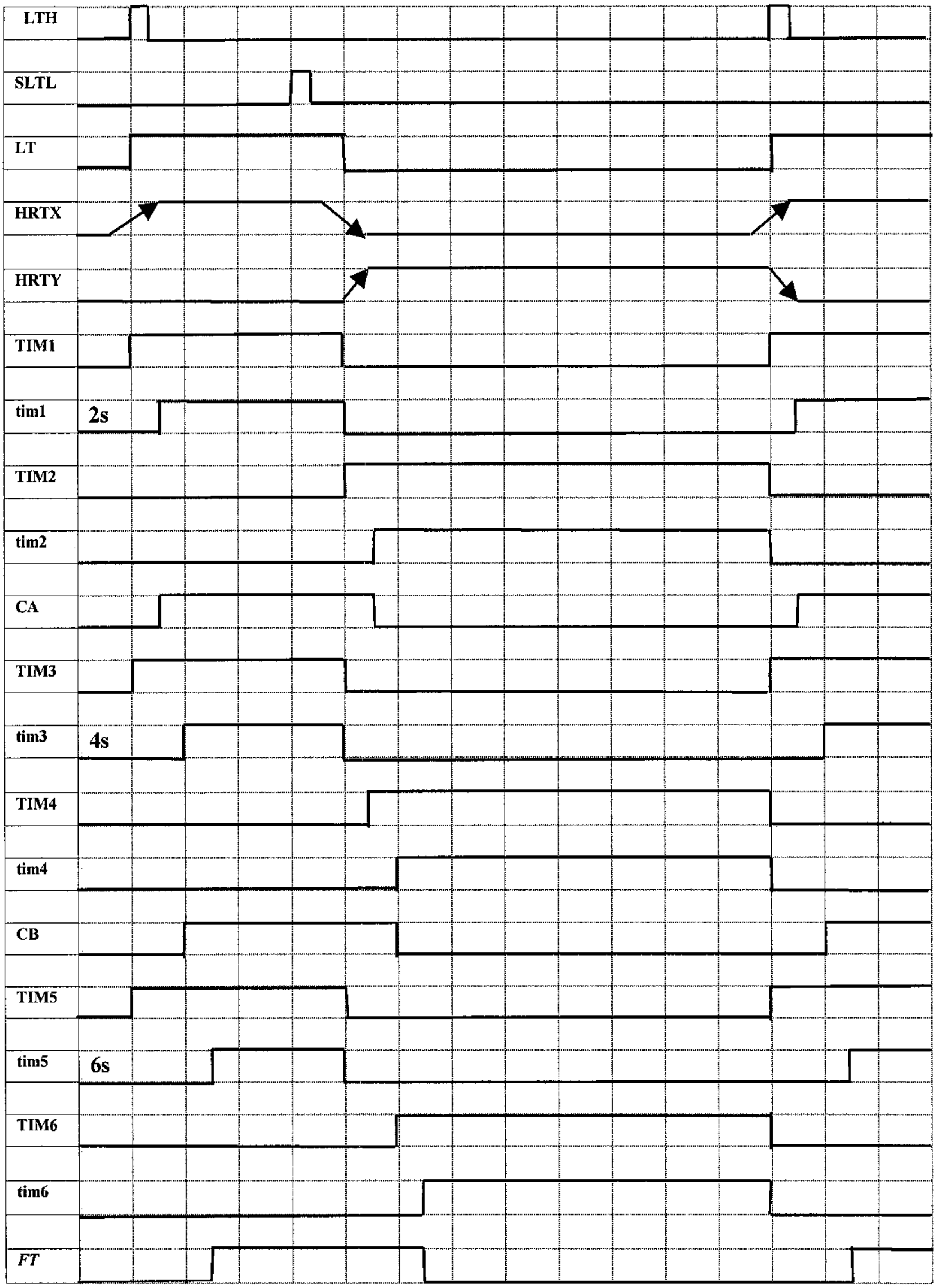


Figure 3.3: Timing Diagram showing Timers & Holding Relays

Figure 3.3 is the timing diagram that correlates to the control sequences of the cascade controller that has been established.

3.3.1.3 Logical Equations

1. **$LT = (SLTH + LT) . \overline{SLTL}$**
2. $HRTx = (SLTH + HRTx) . \overline{SLTL}$
3. $HRTy = (SLTL + HRTy) . \overline{SLTH}$
4. TIM1 = HRTx
5. TIM2 = HRTy
6. **$CA = (tim1 + CA) . \overline{tim2}$**
7. TIM3 = HRTx
8. TIM4 = HRTy
9. **$CB = (tim3 + CB) . \overline{tim4}$**
10. TIM5 = HRTx
11. TIM6 = HRTy
12. **$FT = (tim5 + FT) . \overline{tim5}$**

Where,

SLTL = Switch Level Transmitter Low

SLTH = Switch Level Transmitter High

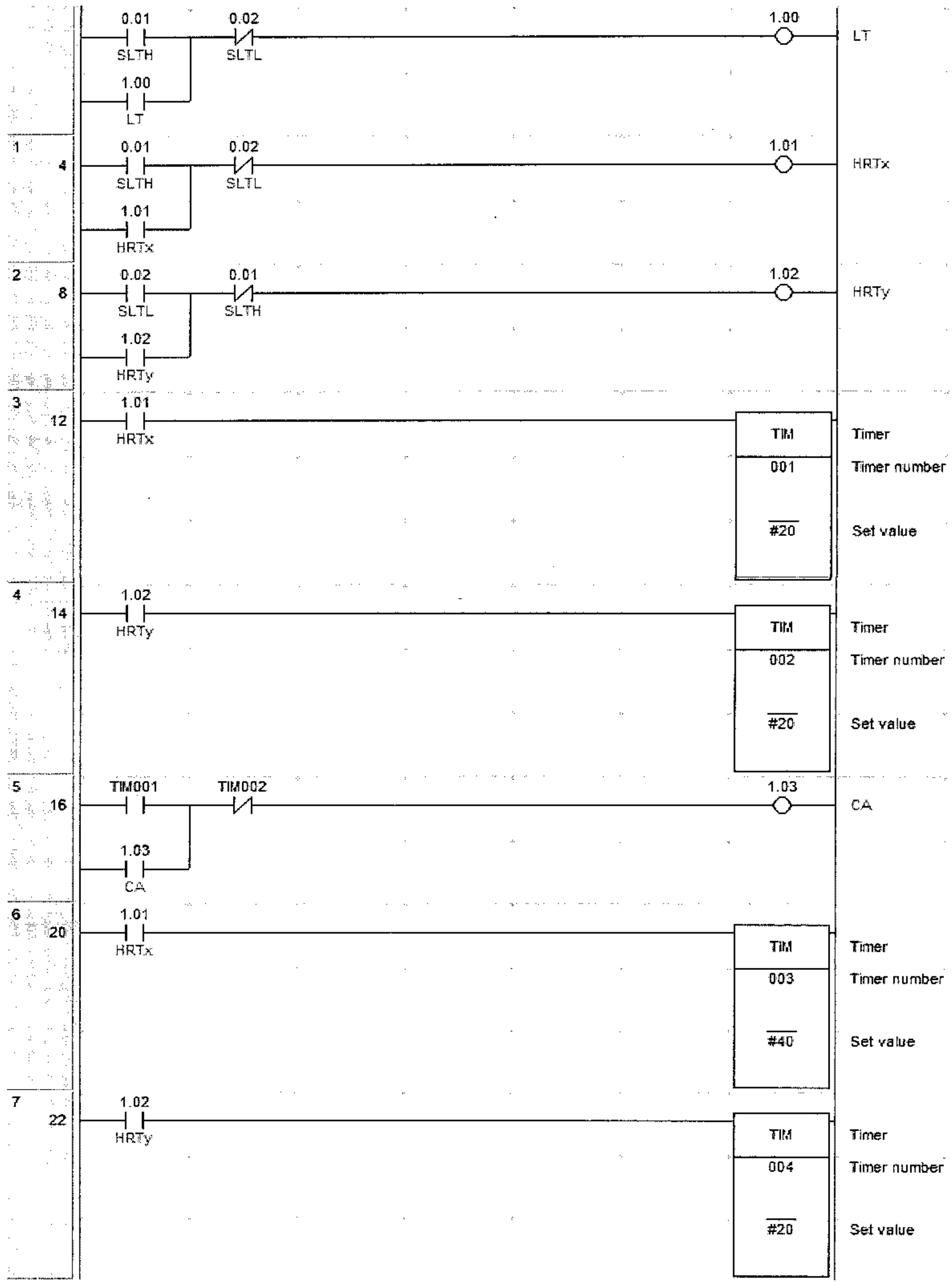
HRTx = HRTy = Holding Relays x and y (internal outputs)

TIM = timer

tim = signifies when the timer is SET

Once the logical equations have been defined the next step is to transform the equations into its ladder diagram. Figure 3.4 shows the ladder logic diagram that has evolved from the process.

3.3.1.4 Ladder Diagram



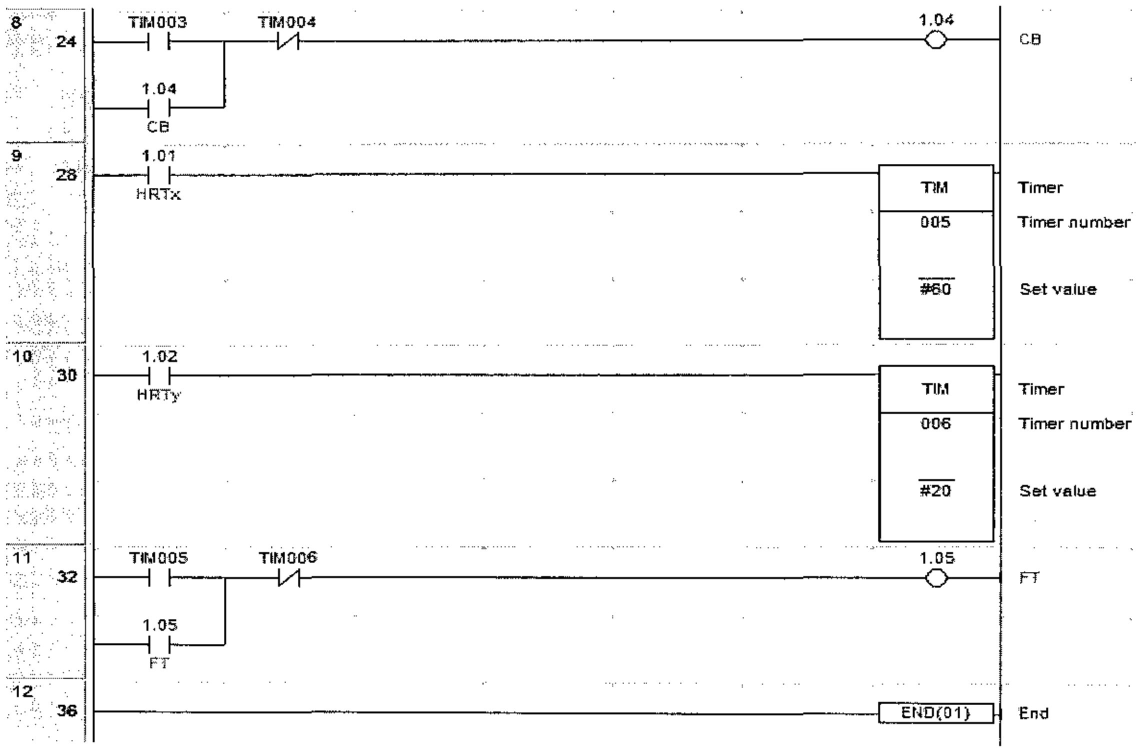


Figure 3.4: Ladder Program of Cascade Control

3.4 SOFTWARE IMPLEMENTATION

3.4.1 ADDRESSING

The correct addressing of the inputs and outputs are essential to the operation of the cascade control system. Each analogue I/O has a specific address. The analog I/O's can use both the **IR** and **DM** memory areas of the CQM1H PLC to operate [3].

❖ **IR memory area**

IR area bits are allocated to terminals on I/O Output Units and Dedicated I/O Units [3]. They reflect the ON/OFF status of input and output signals. Input bits begin at IR 00000, and output bits begin at IR 10000. The I/O addresses specified above are used primarily for Digital I/O's The IR memory area has several working areas that perform different tasks these are indicated in Table 3.1 below [3]:

Table 3.1: IR data areas specification [3]

Range	Function
IR 001 to IR 015	When allocated to Input Units, these bits serve as input bits.
IR 090 to IR 095	When a Controller Link Unit is mounted to the PC, these bits indicate the status of the Data Link.
IR 096 to IR 099	When the MACRO instruction is used, these bits serve as operand input bits.
IR 100 to IR 115	When allocated to Output Units, these bits serve as output bits.
IR 190 to IR 195	When a Controller Link Unit is mounted to the PC, these bits indicate information on errors and nodes in the network.
IR 196 to IR 199	When the MACRO instruction is used, these bits serve as operand output bits.
IR 200 to IR 215	These bits are used by an Inner Board mounted in slot 1.
IR 220 to IR 223	These bits serve to store the analog settings when an Analog Setting Board is installed.
IR 230 to IR 231	When high-speed counter 0 is used, these bits are used to store its present value.
IR 232 to IR 243	These bits are used by an Inner Board mounted in slot 2.

From **Table 3.1** one can see the IR addresses ranging from 232 to 243 are dedicated to the inner board mounted in slot 2 [3]. The Analogue I/O board is connected to slot 2 therefore addresses 232 to 237 specify the addresses for the analogue inputs and outputs used in the PID instruction as shown below in **Table 3.2**.

Table 3.2: Analog I/O addresses [3]

Word	Bits	Function
IR 232	00 to 15	Analog Input 1 Conversion Value
IR 233	00 to 15	Analog Input 2 Conversion Value
IR 234	00 to 15	Analog Input 3 Conversion Value
IR 235	00 to 15	Analog Input 4 Conversion Value
IR 236	00 to 15	Analog Output 1 SV
IR 237	00 to 15	Analog Output 2 SV
IR 236 to IR 243	00 to 15	Not used.

❖ **DM Memory Area**

Data is accessed in word units. As shown below, the read/write part of the DM area can be freely read and written from the program [3]. The rest of the DM area is assigned specific functions in advance (as shown in Table 3.3).

Table 3.3: DM memory assignments [3]

Name			Range
Read/write	All CQM1H CPU Units		DM 0000 to DM 3071
	CQM1H-CPU51/61 only		DM 3072 to DM 6143
Read-only area	Entire read-only area		DM 6144 to DM 6568
		Controller Link DM parameters area	DM 6400 to DM 6409
		Routing table area	DM 6450 to DM 6499
		Serial Communications Board settings	DM 6550 to DM 6559
Error log area			DM 6569 to DM 6599
PC Setup			DM 6600 to DM 6655

The read/write area has no particular functions assigned to it and can be used freely. It can be read and written from the program or Programming Devices. The settings in memory area **DM 6611** (16 bits) determines the operation of an Analog I/O Board mounted in Inner Board slot 2 i.e. by entering certain bit values one can [3]:

- Initialize specific analog inputs
- Set the signal range e.g. **-10V to 10V**, **0V to 10V**, **0V to 5V** or **0mA to 20mA**

The Table **(Table 3.4)** below shows the bit setting in greater detail:

Table 3.4: DM 6611 settings [3]

Word	Bits	Function	Settings
DM 6611	00 to 01	Analog Input 1 Input Signal Range	Set the bit status of the two bits as follows: 00: –10 to +10 V 01: 0 to 10 V 10: 0 to 5 V or 0 to 20 mA
	02 to 03	Analog input 2 Input Signal Range	
	04 to 05	Analog input 3 Input Signal Range	
	06 to 07	Analog input 4 Input Signal Range	
	08	Analog Input 1 Usage Selection	0: Support (use) input. 1: Do not support input.
	09	Analog Input 2 Usage Selection	
	10	Analog Input 3 Usage Selection	
	11	Analog Input 4 Usage Selection	
	12 to 15	Not used.	Set to 0.

From **Table 3.4** one can see that the first 8 bits of DM6611 sets the range of each of the analog inputs the second 4 bits are used to initialize the 4 analog inputs [3].

3.4.2 Test Analog I/O's

In order to ensure that the analog inputs and outputs of the PLC functioned as expected simple ladder program was written and this is shown in Figure 3.5.

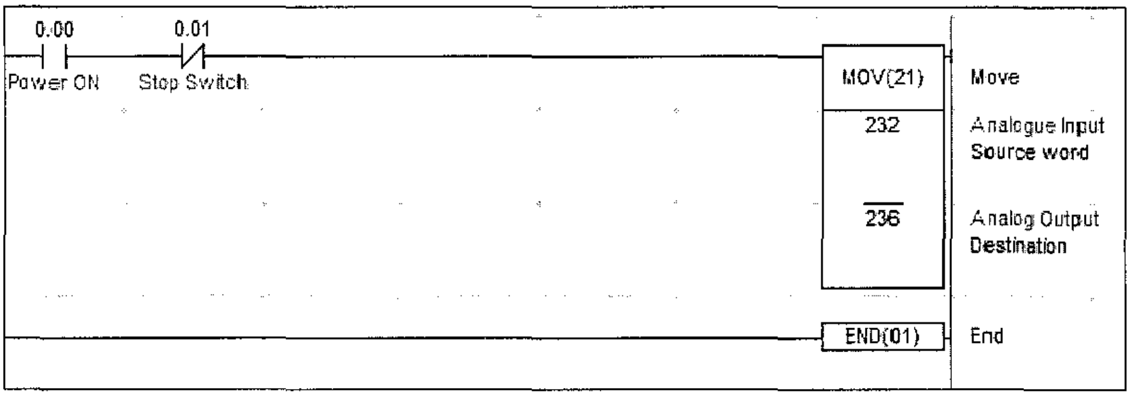


Figure 3.5: Ladder Program testing analog I/O's

The program above has a two digital inputs i.e. **0.00 [START]** and **0.01 [STOP],** these two bits are used to START and STOP the movement of data. The instruction used to move data from the input to the output is the **MOV(21)** instruction. This instruction simply moves one word from the source location to the destination memory area. The instruction only executes once the RUNG is HIGH. In this program the source location is IR 232, which is an analogue, input and the destination location is IR 236, which is an analogue output. The I/O signal range, input and output initialization is setup in the DM memory area (DM 6611) shown below:

Specification of the I/O

- I/O range = 0V to 10V
- Analog Input 1 and Analog Output 1 are used

Table 3.4 shows the bit settings that must be entered into address **DM 6611** Referring to Table 4 above the bit sequence (word) entered into address DM 6611 is:

0000000111111110

bit 15 bit 0

Figure 3.6: Bit sequence entered into address DM 6611

- Bits 12 to 15 are set ZERO
- Bits 9 to 11 are set to ZERO ensuring that analog inputs 2 to 4 are
- Bit 8 is set to ONE therefore initializing analog input 1
- Bits 2 to 7 are set to ONE since inputs are not being used
- Bits 0 to 1 are set to **1 0** setting the range to **0V to 10V**

Note: each of the four analog inputs were tested in this way

3.4.3 The PID Expansion Instruction

❖ **Single PID control Loop**

The aim of this exercise was to test the PID expansion instruction of the CQM1H PLC using the same settings that were used to test the analogue I/O's. This test is needed to verify that the PID instruction does allow the PLC to act as a controller. The ladder diagram developed is shown below (Figure 3.7):

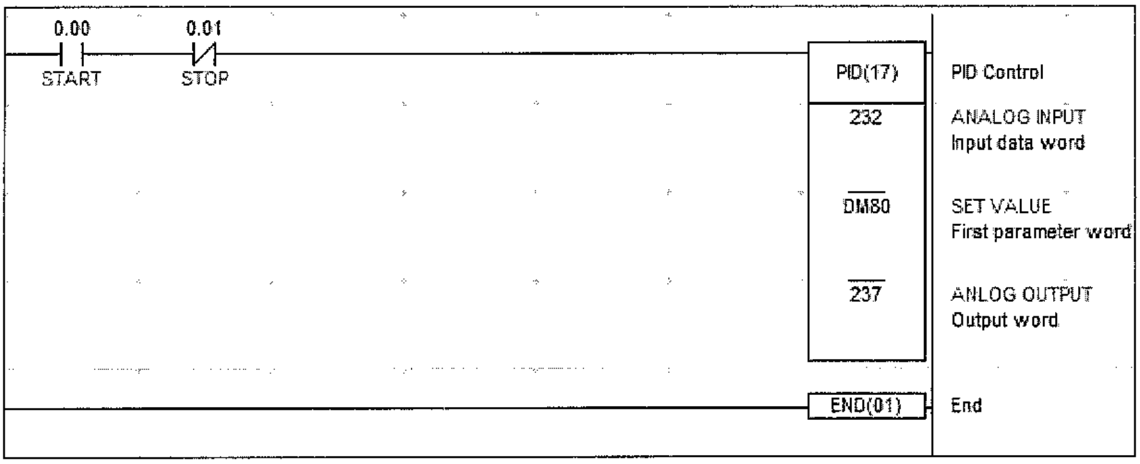


Figure 3.7: Ladder Diagram of a Single PID control Loop

The program above has two digital inputs i.e. **0.00 [START]** and **0.01 [STOP],** these two bits are used to START and STOP the PID controller. The PID calculation is done by the PID expansion instruction (PID (17)). A total of 33 continuous words starting with P1 must be provided for PID (—) to operate correctly (refer to Table 3.7) [3].

The specifications of the PID instruction are given below:

- I/O signal range = 0V to 10V
- Analogue input = IR 232 (Input Data Word)
- Analog Output = IR 237 (Output Data Word)
- The SET VALUE is entered in address DM 80 (First Parameter word)
- The advanced PID settings (i.e. P1-P1+32) (are shown in a table below (Table 3.5):
  - Set value
  - Proportional Bandwidth
  - Integral Time
  - Derivative Time
  - Sampling Period
  - Operation Specifier (reverse/normal operation)

- Output Range
- Input range

Table 3.5: Advanced PID settings [3]

Word	Bits	Parameter name	Function/Setting range
P1	00 to 15	Set value (SV).	This is the target value for PID control. It can be set to any binary number with the number of bits set by the input range parameter.
P1+1	00 to 15	Proportional band width.	This parameter specifies the proportional band width/input range ratio from 0.1% to 999.9%. It must be BCD from 0001 to 9999.
P1+2	00 to 15	Integral time	Sets the integral time/sampling period ratio used in integral control. It must be BCD from 0001 to 8191, or 9999. (9999 disables integral control.)
P1+3	00 to 15	Derivative time	Sets the derivative time/sampling period ratio used in derivative control. It must be BCD from 0001 to 8191, or 0000.
P1+4	00 to 15	Sampling period	Sets the interval between samplings of the input data from 0.1 to 102.3 s. It must be BCD from 0001 to 1023.
P1+5	00 to 03	Operation specifier	Sets reverse or normal operation. Set to 0 to specify reverse operation or 1 to specify normal operation.
	04 to 15	Input filter coefficient	Determines the strength of the input filter. The lower the coefficient, the weaker the filter. This setting must be BCD from 100 to 199, or 000. A setting of 000 sets the default value (0.65) and a setting of 100 to 199 sets the coefficient from 0.00 to 0.99.
P1+6	00 to 07	Output range	Determines the number of bits of output data. This setting must be between 00 and 08, which sets the output range between 8 and 16 bits.
	08 to 15	Input range	Determines the number of bits of input data. This setting must be between 00 and 08, which sets the input range between 8 and 16 bits.
P1+7 to P1+32	00 to 15	Work area	Do not use. (Used by the system.)

For the PID instruction to wok properly it must properly setup i.e. all the parameters mentioned in Table 3.5 must be entered into the same data area. For this ladder program the DM memory area ranging from DM 80 to DM 112 since 33 words are needed by the instruction.

- DM80 to DM86 are user defined depending on the application the controller is going to be used in (i.e. values used to tune the PID controller).
- DM87 to DM112 are used by the PLC to perform the PID calculation

3.4.4 CASCADE CONTROL – LADDER PROGRAM

The final part of the project is to implement a cascade control system, which will be able to control the level of process fluid in a distillation tower. In order to implement this control system two PID controllers are required to form the primary and secondary loops. In the PLC ladder diagram the two PID instructions constitute the primary and secondary controllers as shown below (figure 3.8):

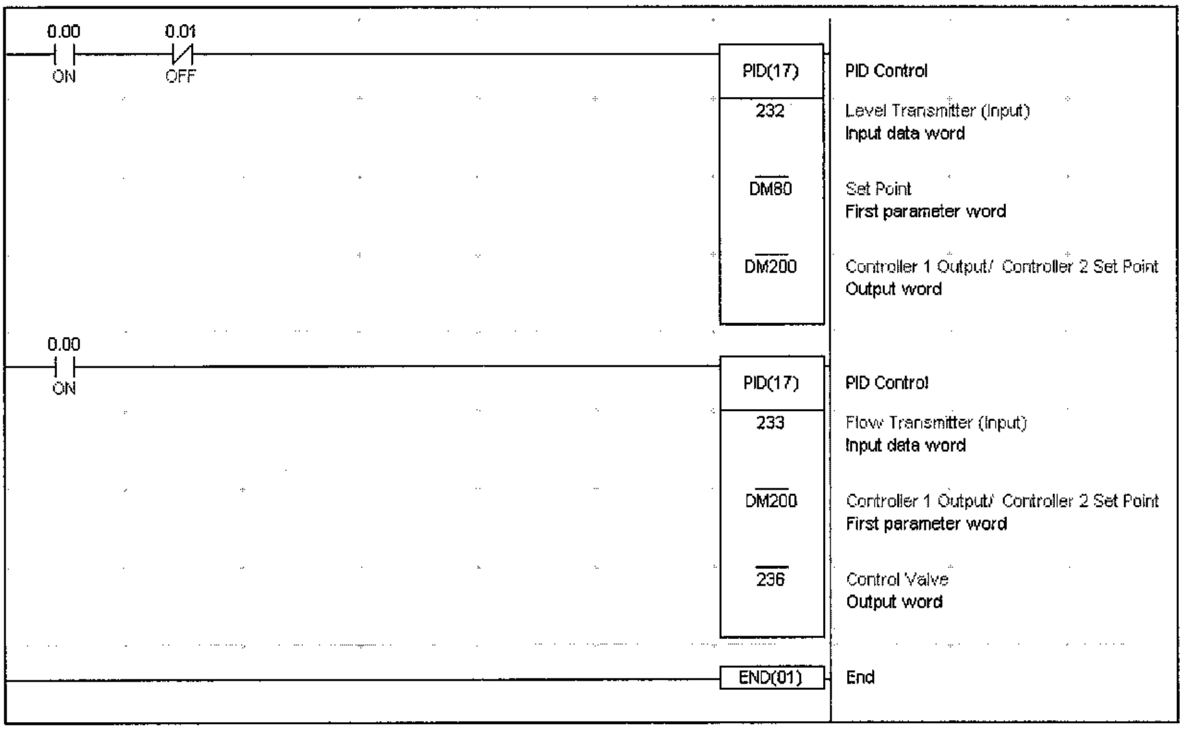


Figure 3.8: Ladder Diagram (Cascade Control)

The 1st PID instruction block is the master controller (Level Controller) and the 2nd PID instruction block is the secondary controller (Flow Controller). The specifications for each block are given below:

➢ **Master Controller**

- **Input** – level transmitter (LT 232)
- **Set Point Value** – value entered in memory area **DM80** (value = 16 bits)
- **Output** – value stored in memory area **DM200** (value = 16 bits)

- **Secondary Controller**

  - **Input** – flow transmitter (FT 233)
  - **Set Point Value** – value taken from memory area **DM200** which is the same memory area where the output of the master controller is stored

DM200 = output (master controller) = set point (secondary controller)

  - **Output** – stored in address **IR236** (analogue output = 4mA to 20mA)

3.4.5 Cascade Control with High and Low Alarms

The program below performs cascade control with the added functionality of a HIGH and LOW level alarm which is capable of responding to an emergency situations i.e. this ladder program (figure 3.9) represents cascade control system with an integrated emergency shutdown system.

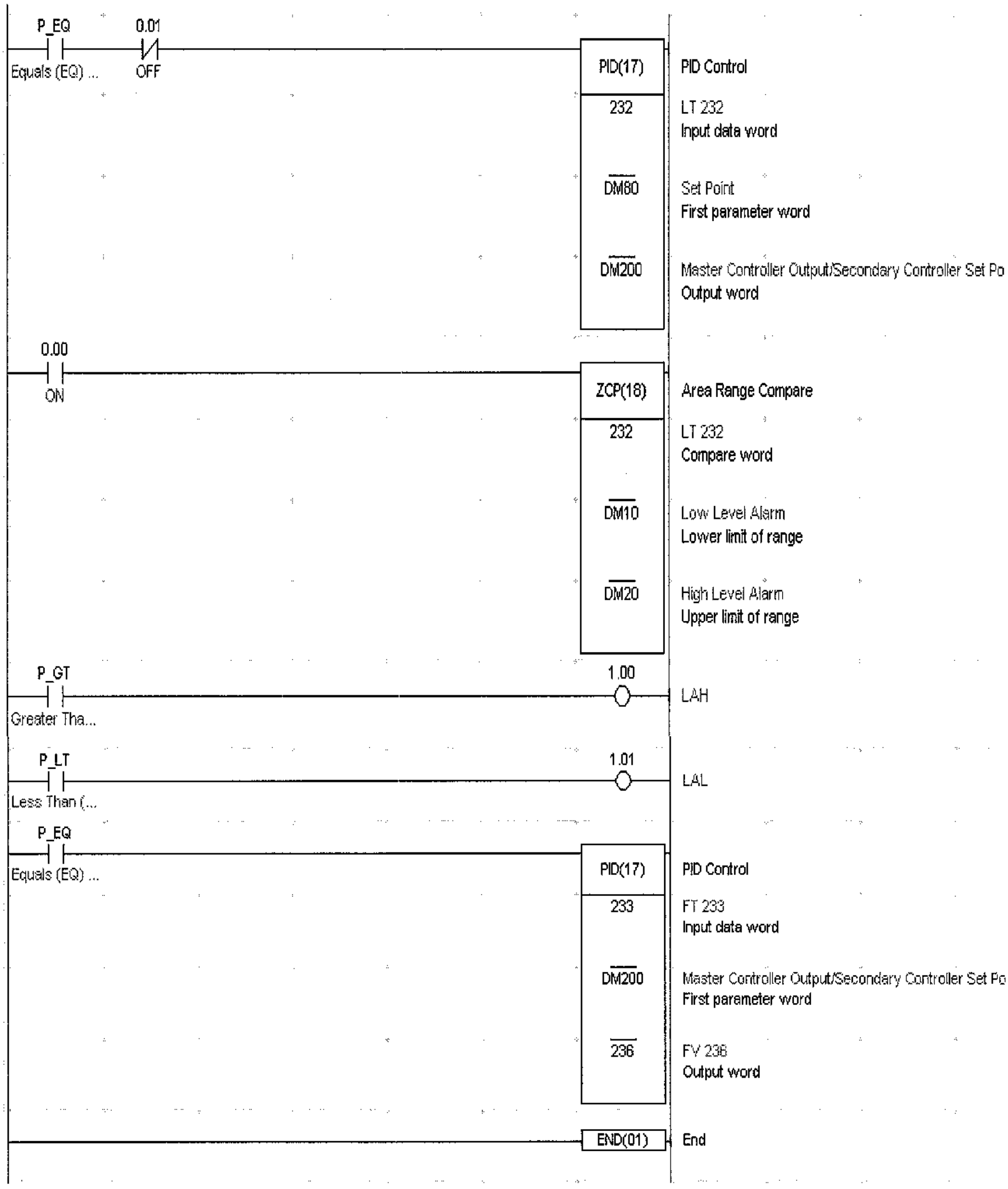


Figure 3.9: Cascade control ladder diagram with HIGH and LOW alarms

The HIGH and LOW limits are detected by the 'Area range control' (figure 3.10) instruction. This instruction allows the user to set the high and low limit value and compares the input value (i.e. level measurement value) with the high/low limit values set by the user.

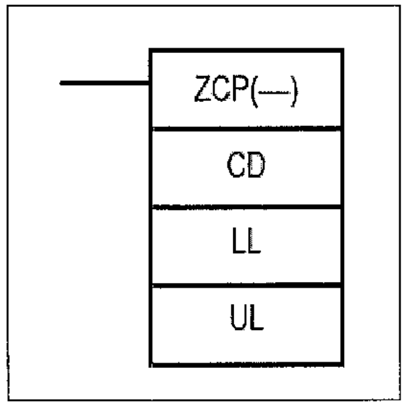


Figure 3.10: 'Area range control' Ladder Symbol [3]

Where:

CD – compare data

LL – lower limit

UL – upper limit

When the execution condition is OFF, ZCP(—) is not executed. When the execution condition is ON, ZCP(—) compares CD to the range defined by lower limit LL and upper limit UL and outputs the result to the GR (greater then), EQ (equivalent), and LE (less than) flags in the SR area [3]. The resulting flag status is shown in the following table:

Table 3.6: Flag status table [3]

Comparison result	Flag status		
	GR (SR 25505)	EQ (SR 25506)	LE (SR 25507)
CD < LL	0	0	1
LL ≤ CD ≤ UL	0	1	0
UL < CD	1	0	0

The flag status bits GR, EQ and LE are used to initialize the alarms, from table 3.6 one can see that the SR flags go HIGH for certain values of CD. Therefore in the program the GR (P_GT) initializes the HIGH alarm, LE (P_LT) initializes the LOW alarm and the EQ flag ensures that when the level is at a nominal value PID control takes place. Therefore when either GR or LE is HIGH, PID control does not occur because the emergency shutdown system takes over.

In an application the two alarm outputs (LAH and LAL) can be connected to safety valves which would stop the distillation tower from having an extremely LOW level or over flowing this is illustrated in the P&ID drawing in Appendix A.

3.5 HARDWARE IMPLEMENTATION

3.5.1 OMRON PLC

The PLC used to implement the project is an OMRON model CQM1H PLC. The CQM1H is a compact, high speed Programmable Logic Controller (PLC) designed for advanced control operations [2]. The PLC has several built in functions both in hardware and software that allow it to implement control applications. The most important module needed to implement cascade control is the Analogue I/O module, which is, be discussed below.

3.5.1.1 CQM1H Analogue Input/Output Module

To implement the control system analogue inputs and outputs are used the Analogue Input/Output Module enables the PLC to receive and output analogue signals. The Analogue I/O Board is an Inner Board featuring **four analog inputs** and **two analog outputs** (figure 3.11) [2]. The signal ranges that can be used for each of the four analog input points are –10 to +10 V, 0 to 5 V, and **0 to 20 mA.**

A separate range is set for each point. The signal ranges that can be used for each of the two analog output points are –10 to +10 V and **0 to 20mA**. A separate signal range can be selected for each point. Either a voltage output or current output is selected using the terminal (pins) connected on the connector [2].

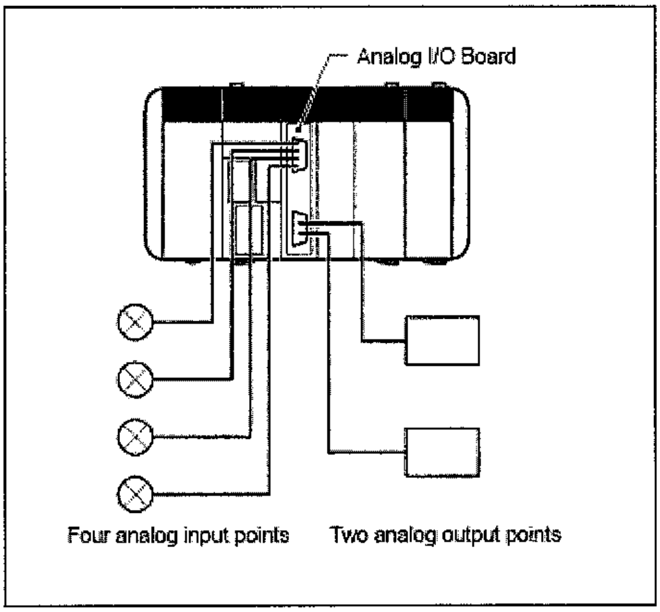


Figure 3.11: Analogue Input/Output Module configuration [2]

The analogue inputs and outputs on the Analogue board are accessed by using two connectors CN1 and CN2. A CN1 connector is used for the 4 analog inputs and a CN2 connector is used for the 2 analog outputs. Pin Arrangement of Connectors CN1 and CN2 are shown in the tables below [2]:

Table 3.7: Pin Arrangement of Connectors CN1 [2]

CN1: Analog Input

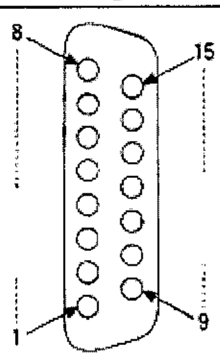
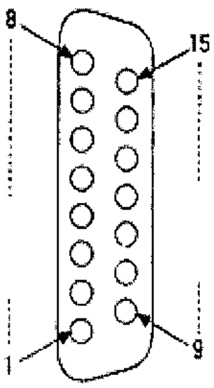
Pin arrangement	Pin No.	Name	Function
	1	V4+	Analog input 4: + voltage input
	2	V4–	Analog input 4: common (– voltage input, – current input)
	3	V3+	Analog input 3: + voltage input
	4	V3–	Analog input 3: common (– voltage input, – current input)
	5	V2+	Analog input 2: + voltage input
	6	V2–	Analog input 2: common (– voltage input, – current input)
	7	V1+	Analog input 1: + voltage input
	8	V1–	Analog input 1: common (– voltage input, – current input)
	9	I4+	Analog input 4: + current input
	10	NC	Not used.
	11	I3+	Analog input 3: + current input
	12	NC	Not used.
	13	I2+	Analog input 2: + current input
	14	NC	Not used.
	15	I1+	Analog input 1: + current input
	Hood	NC	Not used.

Table 3.8: Pin Arrangement of Connectors CN2

Pin arrangement	Pin No.	Name	Function
	1	NC	Not used.
	2	NC	Not used.
	3	I2–	Analog output 2: common (– current output)
	4	V2–	Analog output 2: common (– voltage output)
	5	NC	Not used.
	6	NC	Not used.
	7	I1–	Analog output 1: common (– current output)
	8	V1–	Analog output 1: common (– voltage output)
	9	NC	Not used.
	10	I2+	Analog output 2: + current output
	11	V2+	Analog output 2: + voltage output
	12	NC	Not used.
	13	NC	Not used.
	14	I1+	Analog output 1: + current output
	15	V1+	Analog output 1: + voltage output
	Hood	NC	Not used.

The Analogue I/O is able to accept analogue signals, which represent process variables such as temperature, pressure, level etc. Therefore the Analog I/O Board and Analog I/O functions make it possible for the CQM1H PLC to control a process when it is used in-conjunction with the PID software instruction [2].

3.5.2 Instrumentation

3.5.2.1 Control Valve

A Control Valve is a power-operated device used to modify the fluid flow rate in a process system. It is also a final control element, which means it comes into direct contact with the process. Control valves can operate in three ways depending on its fail-safe position. The control valves fail-safe position describes how the valve will respond to a loss of signal or power. As mentioned the valve can operate in three ways namely:

- **Fail Close:** This means that if there is no power the valve will automatically close therefore the control valve is said to be an "**AIR – TO – OPEN**" valve.
- **Fail Open:** This means that if there is no power the valve will automatically open therefore the control valve is said to be an "**AIR – TO – CLOSE**" valve.
- **Fail in Place:** This means that if there is no power the valve will stay in the same position. This type of control valve requires air to **close** and air to **open** the valve.

The type of valve that is chosen depends on the process requirements because depending on the process application if there is no signal the valve should close, similarly in some applications the valve may need to be open or stay in the same position. Control valves are controlled by a signal that is usually sent by the control system the input signal determines the amount of pressure that the diaphragm receives (i.e. it determines at which position the valve may stay at) e.g. the process may need the valve to be open at 25% therefore the pressure applied and the input signal will be 25% of the maximum if the valve is a fail close valve.

The type of valve used in this project is a 'Globe Valve'. Globe valves are frequently used for control applications because of their suitability for regulating the flow and the ease with which they can be given a specific 'characteristic', relating valve opening to flow e.g. quick acting valve. Below (Figure 3.12) shows a diagrammatic representation of a single seat two-port globe valve. In this case, the fluid flow is pushing against the valve plug and tending to keep the plug off the valve seat. Therefore can be seen clearly that when the Plug is in contact with the Seat the valve is closed i.e. no process fluid can pass through.

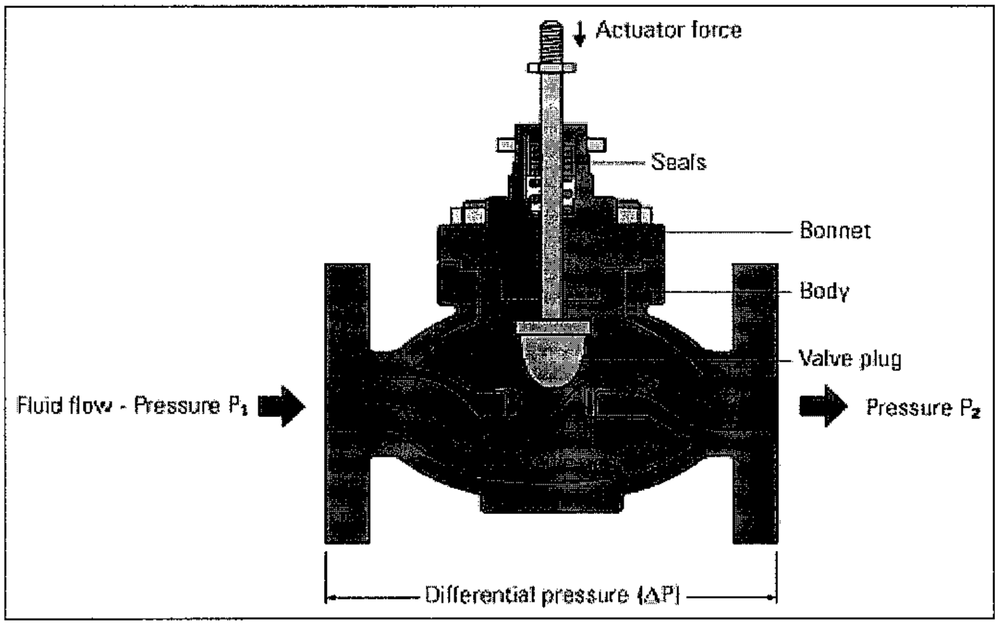


Figure 3.12: Internal structure of a Globe valve (bottom half)

3.5.2.2 Transmitters

❖ **Level Transmitter**

In this project differential pressure (D/P) transmitter can be used to measure the process fluid level in the distillation tower. The D/P transmitter can transmit the head pressure that the diaphragm senses due to the height of the material in the vessel multiplied by a density variable (static pressure measurement). This method is used for both open tanks and closed tanks.

Since a distillation tower is closed to atmosphere the method by which level can be measured is the called dry leg measurement. In the dry leg measurement technique a d/p transmitter is connected to the closed tower; the low-pressure tap is the pressure of the gas above the liquid in the upper part of the tower. The pressure of the gas is also applied to the high-pressure tap at the same time. Therefore when taking the pressure differential, it cancels out and so does not affect the transmitter output. If condensation from the gas in the upper part of the tank collects inside the tapping tube, the low pressure tapping pressure in the tube will change and the output of the d/p transmitter will be affected. To avoid this, the condensation is collected in a drain pot.

The following relationship exists in a closed tank:

- **Pressure differential:**

$$PH - PL = d \times g \times (H + hl)$$

PH	= high pressure tapping value
PL	= low pressure tapping value
d	= density of the liquid
H	= distance between the surface and the minimum liquid level h
h1	= distance between the minimum liquid level and pressure detector.

- **Flow Transmitter**

Differential pressure flow transmitters are commonly used in the plant to measure the flow rate of the process fluid; it has a sealed capacitance-sensing module, which allows direct electronic sensing. Differential capacitance between the sensing diaphragm and the capacitor plates is electronically converted to an output current signal of 4mA to 20mA. The **SMART D/P transmitter** is an electronic transmitter that can communicate with the HART communicator i.e. it can be calibrated using the HART communicator. The flow meter measures the differential pressure across a primary flow element which is usually a orifice plate which is placed in a pipe line i.e. the orifice plate creates a differential pressure across it self which is proportional to the flow rate of the process fluid. This type of flow meter is suitable to use in the cascade control system.

3.5.3 Hardware Setup

The diagram in Figure 3.13 shows the basic connections made between the PLC and field instrumentation when a cascade control loop is being implemented. The level and flow transmitters both transmit their 4mA-20mA measurement signals to the analog I/O board of the PLC via the connector CN 1. This connector is capable of connecting 4 inputs (transmitters) to the analog I/O board. The output signal of the PLC is carried to the positioner via connector CN 2. The positioner then converts the current signal to an equivalent pneumatic signal (3psi-15psi), which in turn manipulates the valve. Connector CN 2 is capable of carrying two analog output signals from the PLC to the final element. Refer to **Appendix B** to view the loop diagram of the cascade control system

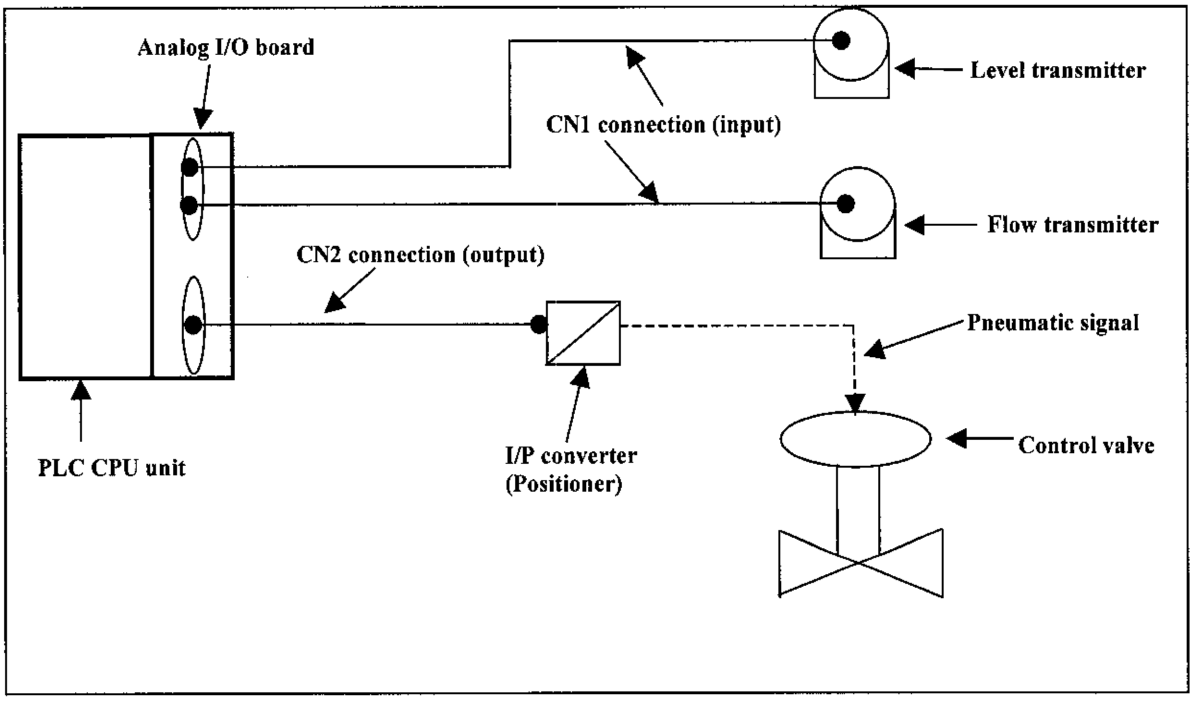


Figure 3.13: Connections between the PLC and field instrumentation

3.5.4 IMPLEMENTATION OF SINGLE LOOP CONTROL ON A PHYSICAL PLANT

Single loop level control was implemented on an open tank system using the PLC PID controller. The control loop consisted of a level controller (LIC 101), smart differential transmitter LT 101 (controlled variable), control valve FV 101 (manipulated variable) and pump (PC 101). Water was pumped from a water trough to the open tank via the pump. The P&ID (figure 3.14) below shows the open tank system.

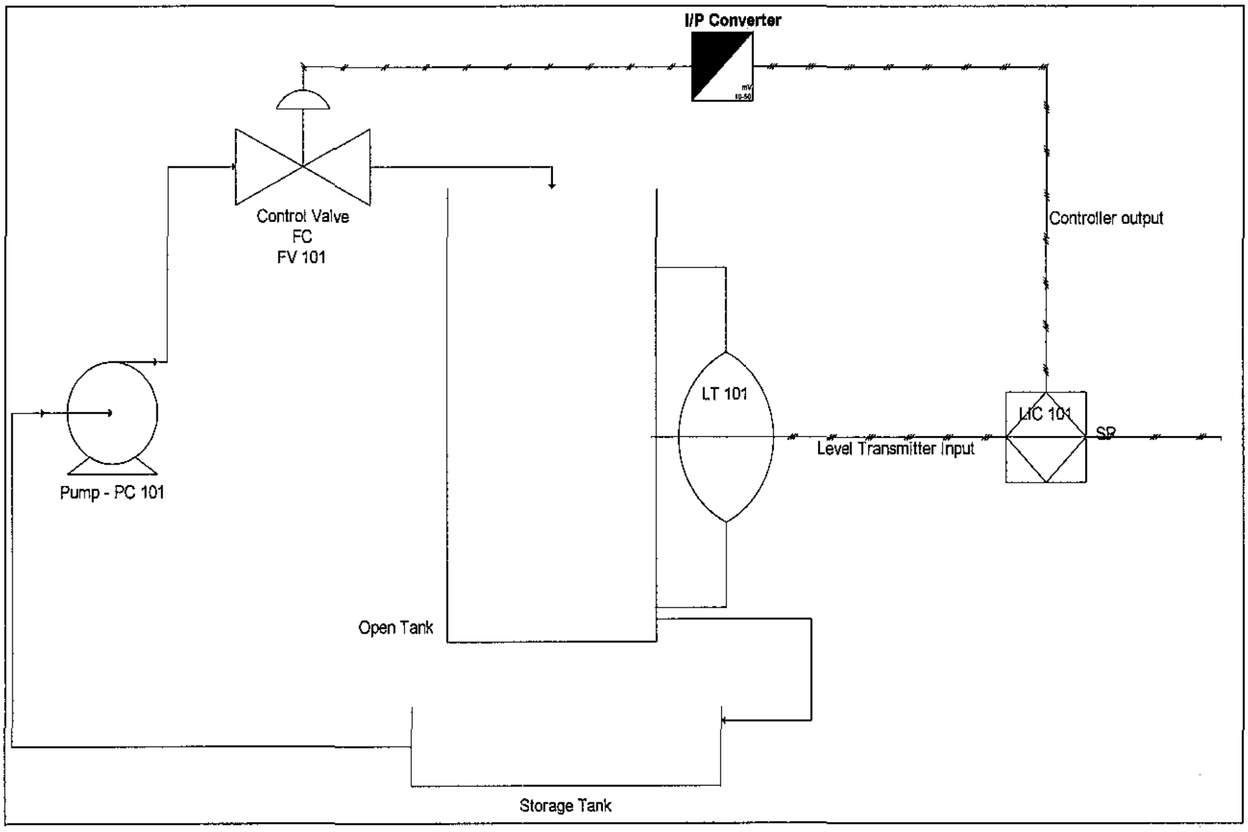


Figure 3.14: P&ID of an open tank system

The pump PC101 pumps the water from a storage tank into the open tank via the fail close feed valve FV 101. The differential transmitter LT 101 measures the level in the tank and supplies an input to the level controller LIC 101. The user sets the setpoint. The controller LIC 101 manipulates the control valve FV 101 in order to ensure that the level reaches the set point. The ladder program of the controller LIC 101 is shown below (figure 3.15). The controller is in reverse mode therefore when the level is LOW the valve opens and when HIGH the valve closes.

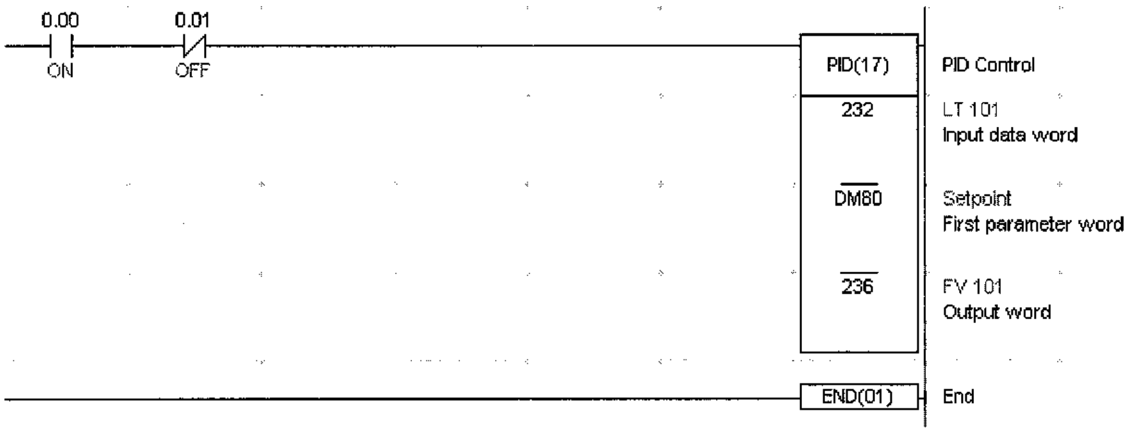


Figure 3.15: Ladder program of level control system

CHAPTER 4

RESULTS & DISCUSSION

4.1 EFFECT OF PROPORTIONAL BAND (PB) ON THE CONTROL SYSTEM

The effect of the proportional band (PB) on the performance of a control system is significant since it determines the proportional gain (Kc) of the controller. The proportional gain determines how aggressively the controller output reacts to an input disturbance. The aim of this experiment is to test the PLC PID controller in-order to verify that it reacts appropriately to a change in PB (i.e. does the controller apply the correct gain value when performing the PID calculation). The values of PB were selected to be 20%, 50% and 80%. In each case the controller (Kc) is calculated using the formula [4],

$$\boxed{Kc = \frac{100\%}{PB}}$$

The controller set point is set to 50% which is equivalent to 12mA therefore there will only be a change in controller output when the input signal is above 12mA. The control valve opening is the monitored variable i.e. the output signal from the PLC is able to open and close a physical valve percentage opening at the correct output signal values.

➢ For PB = 20%

Table 4.1: Table of controller input and output values for PB = 20%

Controller input (mA)	Controller output (mA)	% Valve opening
12.143	2	0
12.423	4	2
12.636	6	15
12.826	8	25
13.033	10	40
13.233	12	55
13.433	14	70
13.633	16	80
13.833	18	90
13.963	20	100

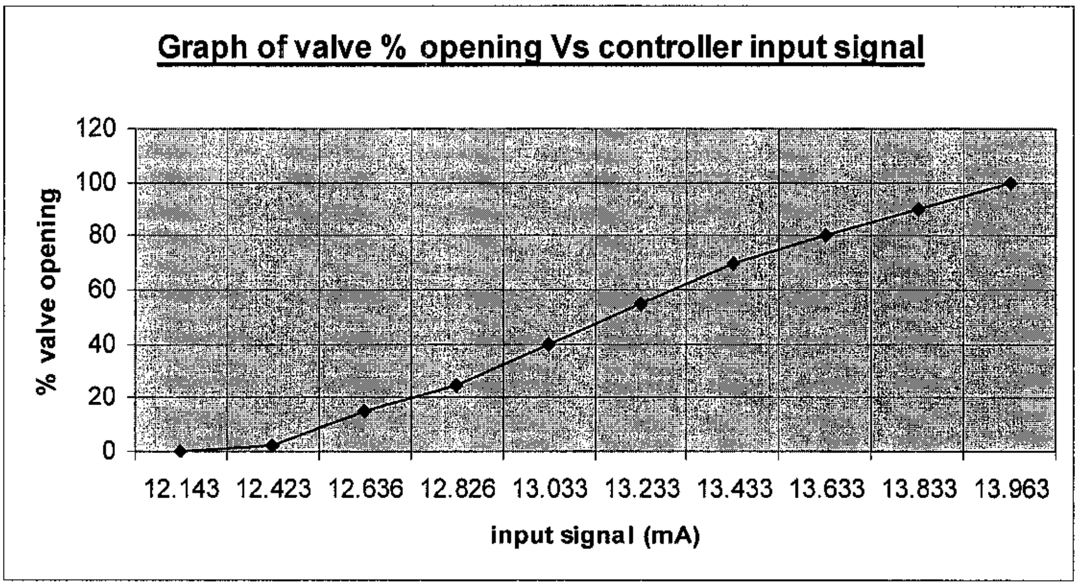


Figure 4.1: Graph of % valve opening Vs controller input signal

Controller gain is

$$Kc = \frac{100\%}{20\%} = 5$$

The graph in (Figure 4.1) indicates that the valve only begins to open when the input signal is significantly above 12mA. The valve is fully open at 13.963 mA and any input above this value will not have an effect on the controller output. Therefore for an input of 13.963 mA the output of the controller output has reached the maximum i.e. 20mA.

➢ For PB = 50%

Table 4.2: Table of controller input and output values for PB = 50%

Controller input (mA)	Controller output (mA)	% Valve opening
12.703	2	0
13.003	4	0
13.603	6	20
14.063	8	30
14.603	10	40
15.063	12	52
15.553	14	65
16.063	16	80
16.583	18	90
16.883	20	100

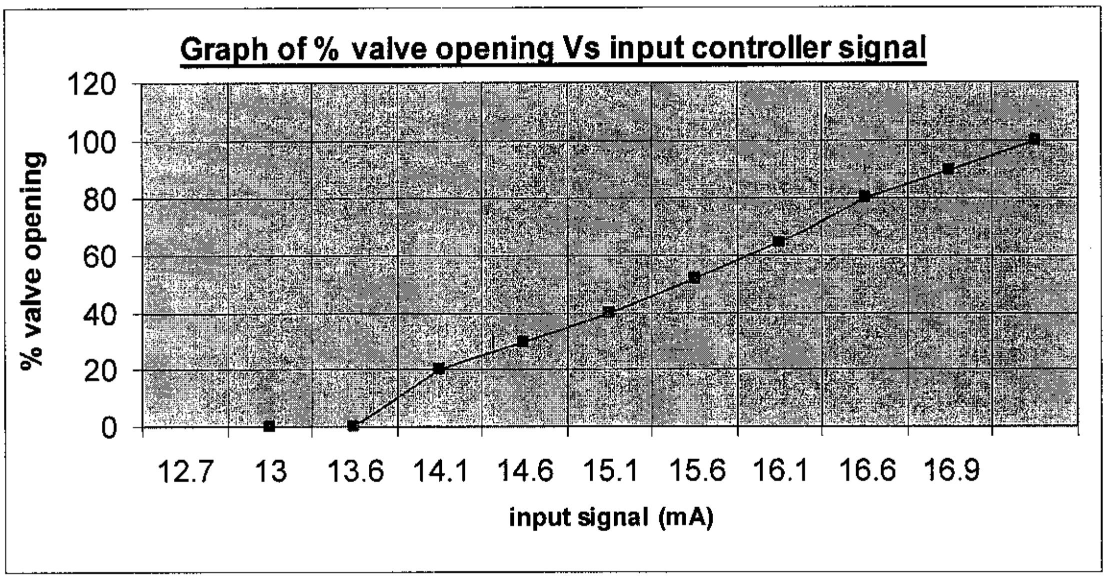


Figure 4.2: Graph of % valve opening Vs controller input signal

Controller gain is

$$Kc = \frac{100\%}{50\%} = 2$$

The valve is fully open at 16.883mA therefore any input above this value will not have an effect on the controller output. Therefore for an input of 16.883mA the output of the controller output is maximum i.e. 20mA.

- For PB = 80%

Table 4.3: Table of controller input and output values for PB = 80%

Controller input (mA)	Controller output (mA)	% Valve opening
12.873	2	0
13.773	4	2
14.573	6	20
15.273	8	30
16.123	10	40
16.923	12	50
17.723	14	62
18.523	16	80
19.323	18	90
19.981	20	100

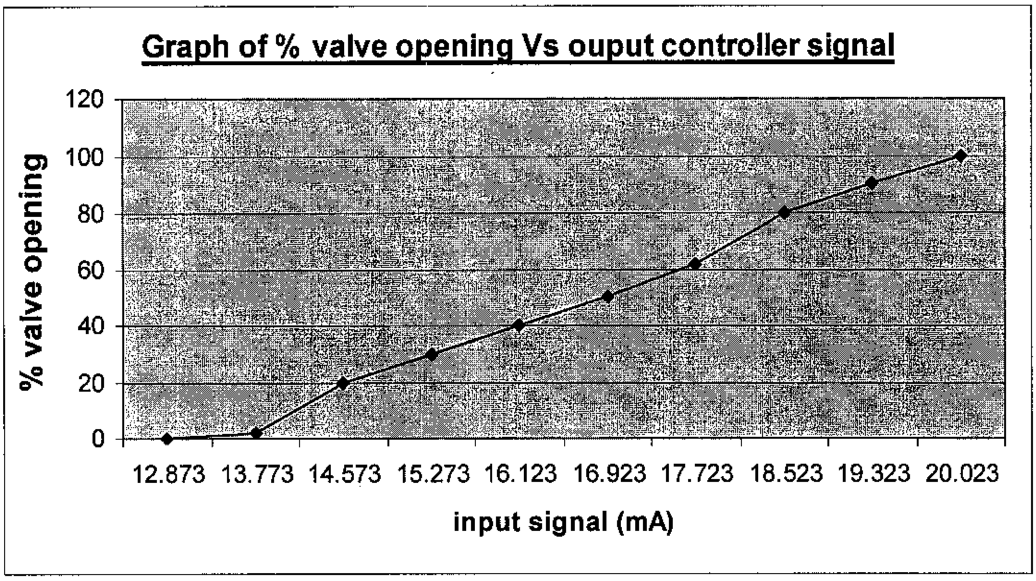


Figure 4.3: Graph of % valve opening Vs controller input signal

Controller gain is

$$Kc = \frac{100\%}{80\%} = 1.25$$

The valve is fully open at 19.981mA therefore any input above this value will not have an effect on the controller output. Therefore for an input of 19.981mA the output of the controller output is maximum i.e. 20mA.

4.2 DISCUSSION

4.2.1 DISCUSSION OF PID TUNING

The ability to tune the primary and secondary controllers is limited due to the fact that there is no physical plant that the system is attached to. Therefore it is not possible to tune the controllers using the standard techniques such as the Ziegler and Nichols PID tuning method [5]. The Ziegler and Nichols PID tuning method requires the values of process gain (Kp), rise time of the process (τ) and the dead time of the process (θ) be known and these can only be determined by getting the process reaction curve of the physical plant.

The cascade control system developed in this project has been tested using calibrators that simulated the signals of the level and flow transmitters (i.e. the calibrators were used to supply the 4mA-20mA input signals to the respective controllers). The tests conducted showed satisfactory results:

- The primary controller's output determined the secondary controllers setpoint
- The outputs of both controllers reflected the values of PID i.e. when the PID values were changed the controller outputs showed an appropriate change

Only the controller gain (Kc) of the controllers could be quantitatively measured since the input and output signals could be measured and compared to determine if the controller applies the correct gain to the input value. The results of these tests were satisfactory since as the controller gain was increased from 1.25 to 5 the output of the controller reached its maximum value sooner i.e. it reached its maximum (100% open) at lower values of the input signal. Therefore as the gain increased smaller input signals were needed to cause a major change in the output signal.

4.2.2 Implementation Of Single Loop Control On A Physical Plant

The implementation of single loop level control on a physical plant was successful i.e. the PLC controller managed to perform PID control. However due to the lack of trends on the system behavior (e.g. process reaction curve) the PID controller could not be tuned using recommended PID tuning methods such as Ziegler Nichols. The controller was tuned by observation therefore it was difficult for the level to reach set point the end result is that there was an offset between the setpoint and actual level.

4.2.3 Cascade System

Notably, there was a major issue major that was identified at the beginning of the project i.e. Configuration of the OMRON PLC to accept a variable analogue input and to supply a variable 4mA to 20mA signal so that it can control the final element. The configuration has been made possible due to the availability of the following features:

- The OMRON CQM1H PLC has an Analogue module that is able to receive and supply analogue signals (4mA to 20mA).
- The CX-programmer software has a built-in PID expansion instruction that therefore allows the user to program the PLC to behave like a controller.

The project focuses on the controlling of the level of a distillation tower as shown below Figure 4.4. The PLC is used to as the primary and secondary controllers of the cascade control loop. The inputs to the controllers are defined as follows:

1. **Primary Controller Input:** is the level measurement of the Distillation Tower (LT)
2. **Secondary Controller Input:** Is the flow rate (FT) of the process fluid, flowing out of the distillation tower.

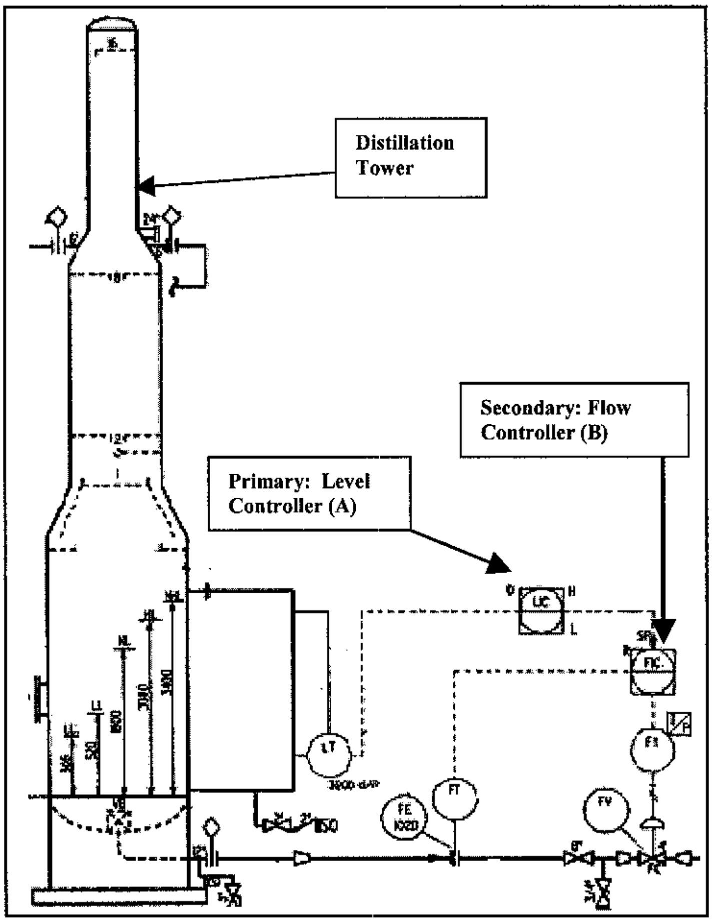


Figure 4.4: Project configuration (Level Control of a Distillation Tower)

Since it is not feasible to implement the exact system and the necessary equipment is not available one alternative is to have the inputs to the controllers simulated. The outputs of the system are defined as follows:

1. **Primary Controller Output:** will be the set-point (SP) of the secondary controller
2. **Secondary Controller Output:** will control the final element (FV) (control valve), which will control the flow rate out of the Distillation tower. An actual control Valve will be used for this purpose.

CHAPTER 5

CONCLUSION

With proper planning and dedication, the objectives of this project have been met. The project has achieved its objective of implementing a cascade control loop using a PLC. Although no working model of the cascade control loop was made the simulations and testing conducted have proved that the PLC is capable of implementing a cascade control loop. The analogue I/O module (hardware) of the OMRON PLC combined with the PID expansion instruction of the CX-programmer (software), allowed the controllers to be designed and PID control to be implemented. The final cascade system had an emergency shutdown system integrated into the cascade loop, which increased the safety of the system.

The focus of this project was to prove that a PLC is capable of performing PID control and that a PLC can be used in small scale plant applications instead of a complex DCS system. This has been proven by looking at the following facts: determining the two system's strengths and weaknesses and proving that the PLC is capable of performing continuous process control applications. The PLC was found to be cheaper, less complex, more reliable and easier to program than a DCS system. The fact that a PLC can work as a stand alone unit (i.e. does not require a complex network of computers) is important in small scale applications since it is not economical to build an entire control room in-order to implement and monitor a few control loops. The PLC also has many peripherals that can be added to enhance its performance e.g. graphical interface capability.

The simpler PLC system is a more viable option than a complex DCS in small-scale plants where continuous process control applications occur.

CHAPTER 6

RECOMMENDATIONS

The PLC control system developed is capable of controlling a process variable (e.g. level) in a small-scale plant. However in-order to make the system user friendly for plant operators a graphical interface should be developed. The interface should show the plants major equipment as well as the relevant values of the process variables being controlled. This interface can be created using visual basic.

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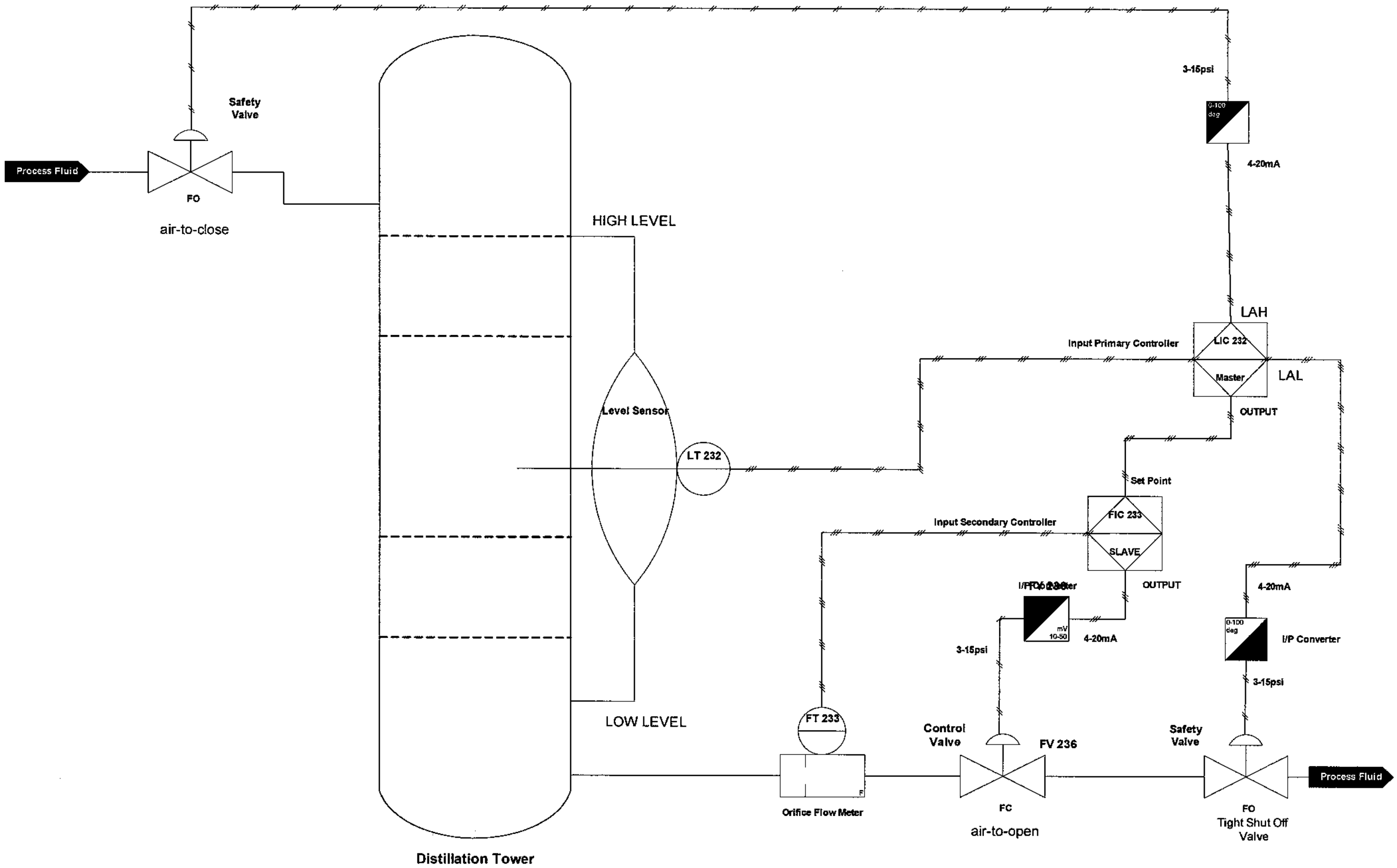
APPENDICES

APPENDIX A

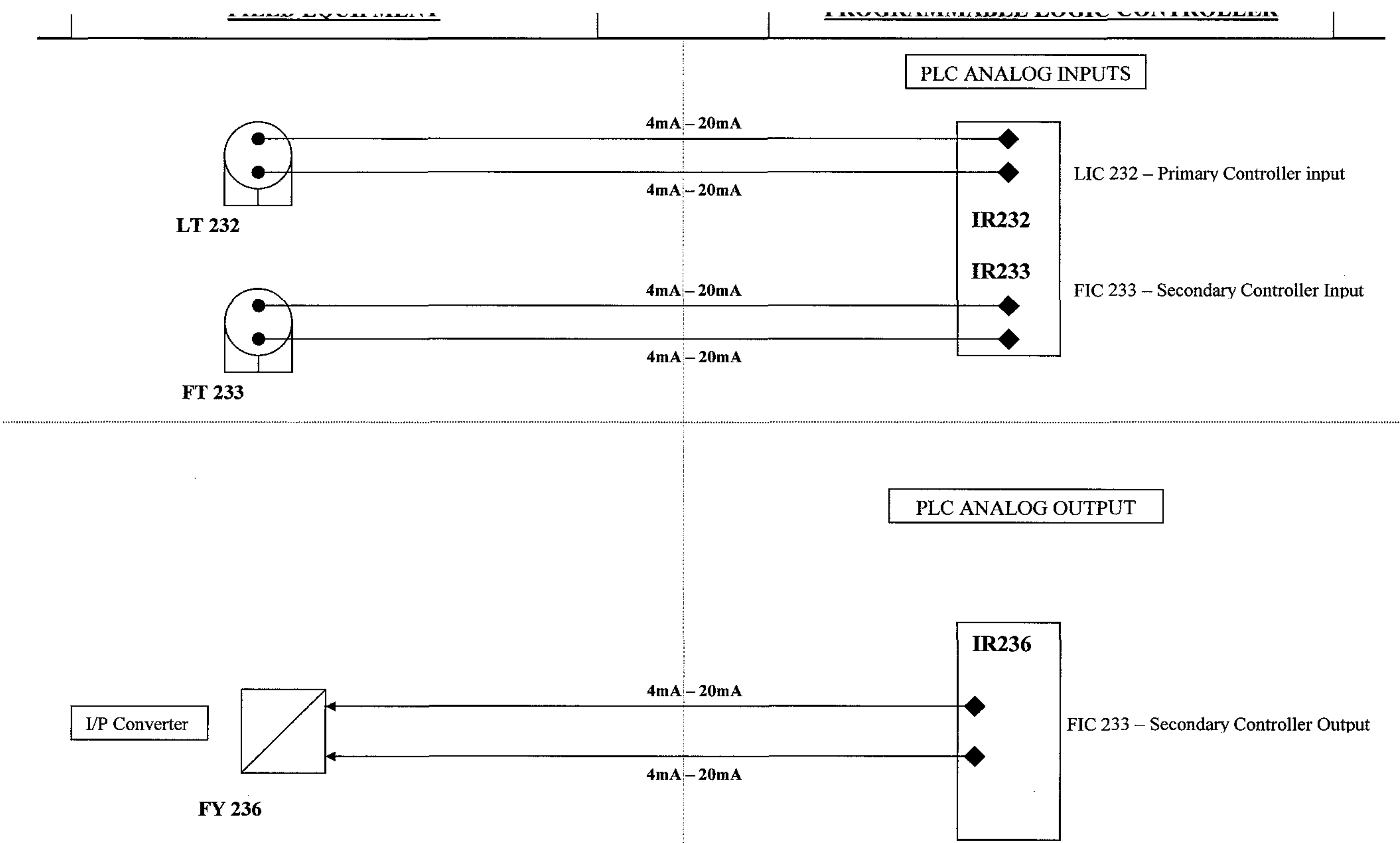
P&ID OF THE CASCADE CONTROL SYSTEM

Cascade Control P&ID



APPENDIX B

LOOP DIAGRAM



NB: Converter supplies equivalent pressure signal to **FV 236 (3-15psi)**