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Design of didactic test bench to verify the reliability of components and systems

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List of Acronyms:

A/D	Analog to Digital
ALU	Arithmetic Logic Unit
CMP	Comparator
CODESYS	Controller Development System
CPU	Central Processing Unit
DC	Direct Current
ExST	Extended Structured Text
FBD	Functional Block Diagram
GE	Greater than or Equal to Comparator
HMI	Human Machine Interface
IL	Instruction List
IP	Internet Protocol
IR	Infrared
LD	Ladder Diagram
MTTF	Mean Time To Failure
NC	Normally Closed
NO	Normally Open
PD	Proportional and Derivative
PI	Proportional Integral
PID	Proportional Integral Derivative
PLC	Programmable Logic Control
PWM	Pulse Width Modulation
RAM	Random Access Memory
ROM	Read-Only Memory
RTD	Resistive Temperature Detector
SCADA	Supervisory Control Aid Data Acquisition
SFC	Sequential Function Chart

SR	Set Reset Flip Flops
ST	Structured Text
TCP	Transmission Control Protocol
TMR	Timer Latch
WSN	Wireless Sensor Network
Z-N	Ziegler Nicholas method

Abstract:

In the fast-developing industrial world, the abilities of automated machines have gone beyond imagination. The reliability of the components and systems has always been an important parameter to keep up the productivity to a higher level. The extensive application of the Programmable Logic Controller in the industries have ensured high level of reliability and safety of the automated system. The main objective of this thesis is to design a didactic test bench that could be used to study and analyse the concept of reliability (Probability of success). The didactic test bench should have an experimental setup consisting of many physical components (sensors, actuators, microcontrollers, etc.) whose working can be experimented with the concept of reliability. But, due to time constraint, the system design and software simulation of the system was done in this thesis, instead of the complete physical model. The system designed for the didactic test bench is basically a chemical mixing experimental setup that is controlled by a Programmable Logic Controller (PLC). Using the proposed system, the practical knowledge about the working of automated control systems and the effect of reliability on such systems are acquired. This thesis is mainly focused on providing hands-on experience for chemical engineering students involving PLC based automatic chemical mixing. The system is designed in a unique way that it is possible to redesign the whole system by adding new inputs, outputs and implementing advanced automatic control techniques. This could be achieved only with the help of PLCs. PLCs are widely used in process control systems due to its ability for being user programmable, it can be programmed according to the needs of the users. The computational abilities of the PLC allow for more sophisticated and complex control. The easy troubleshooting makes programming much simple and therefore reducing downtime of the working system. In this thesis, the design comprises of various inputs like level indicators and temperature sensors and various outputs like heater control, solenoid valves, turning on and off of pumps and agitator. This thesis is simulated in real-time with the help of freeware PLC programming software's CODESYS and WPL SOFT by DELTA. This project is designed in such a way that the students could understand the concept of automated working of chemical mixer in industry. This thesis is the first step towards achieving the complete set of 'Design of didactic test bench for testing the reliability of components and system' which could be achieved through further studies and developments to the proposed system.

Keywords: Reliability, Didactic test bench, Chemical Mixer, Programmable Logic Controllers.

1 Introduction:

1.1. Overview of the Industrial Control System:

In today's industrial scenario the temperature, pressure, level and flow are the four parameters that are required to be controlled for any process control system to work non-stop. The above four parameters requires constant supervision and control, for smooth operation. These supervision and control in the process and chemical industry is done with the help of programmable logic controllers. The PLCs can be programmed to perform any required specific operation. The high level automation carried out in process control industry involves the use of PLC along with complex control techniques like PI (Proportional Integral) control, PID (Proportional Integral Derivative) control and PD (Proportional and Derivative) control. These control techniques are implemented in the form of controllers that are connected to the PLC and the PLC uses the control logic in the controllers to perform the specific operating requirements. PID controller is the most widely used controller in the automation industry.

In most process control operations certain variables are supposed to be maintained in the specific desired range, for example, the temperature in any chemical process is important to maintain to produce the desired output. The accuracy of process control system is crucial as it helps to improve the productivity of the process and thus preventing the occurrence of any irreversible damages to the equipment, safety of the operators, and damage to the environment.

In industries where automation is implemented, it is usually done with large number of PLCs doing specifically defined control operations independently and those PLCs can be monitored with the help of SCADA or HMI systems. SCADA stands for Supervisory Control and Data Acquisition and HMI stands for Human Machine Interface. The job of the above two supervisory soft wares is the visualization of all the operations carried out by the networked PLCs and acquiring data from the field and stores them in the database. These data can be used for future analysis of the automation network and troubleshooting.
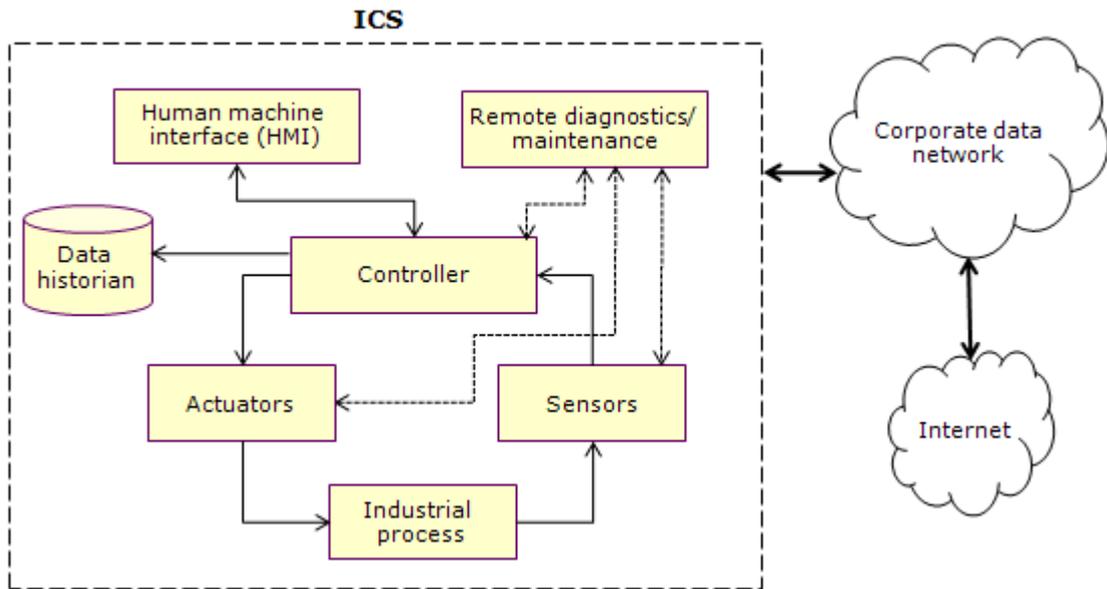
Figure 1: Industrial Control System [17].

The process control system is widely used in different industrial sectors such as, chemical, petro chemical, waste water management, food production and pulp and paper production. In any control system, controller plays the vital role controlling the operating conditions of the system. PLC is widely used as the mail controller in many industries due to its advantages, such as, high reliability, faster response, easy troubleshooting, simple programming options and overall low cost implementation and maintenance.

1.1.1. Overview of Programmable Logic Controllers (PLC):

The programmable logic controller is a digital computer specially designed for industrial control purposes. It can work in several different environmental conditions and achieve continuous or discrete control goals in real time.

The first programmable logic controller was created by Modicon in the year 1968 [1]. The idea for a PLC aroused from the need to replace the relay logic that was used in the industries in the 1960's to automate ON/OFF process by energizing or de-energizing the electromagnetic fields. The first PLC by Modicon was the model 084 and the upgraded version was 184 which was basically working on the Boolean algebraic principle which means one variable has only two states (True or False). Thus the first generation of PLC was

able to achieve only the ON-OFF control. The model 284 by the Modicon was the first controller with a microprocessor and distributed control technology.

Figure 2: Modicon 184, second generation of PLC by Modicon [18].

Later on, the PLC evolved through time and got more advanced functions such as timers, counters, memory set and memory reset, mathematical computations etc. Another significant feature of the PLCs is that it can deal with analog signals directly which led to the simplified control system design. With the analog inputs and outputs in the PLC, monitoring and management of the real time data was efficient. This also increased the system response time and easy fault detection. Furthermore the cost of implementation of the PLC is also low compared other types of control systems.

PLC consists of 5 common blocks, they are:

- Rack assembly (for mounting inputs, outputs, power supply, processor unit).
- Power supply (usually 24 V DC)
- Input/Output modules
- Central Processing Unit (CPU), it controls all the operations.
- Programming device

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At present, there are many PLC manufacturers in the competitive global market, each producing many types of PLCs depending on the functions, cost, size and operations it intends to do. Many manufacturers also do operation specific control system design.

The top global players in manufacturing PLCs are:

No	Manufacturer
1	Siemens
2	ABB
3	Rockwell Automation
4	Mitsubishi
5	GE- Fanuc
6	Omron
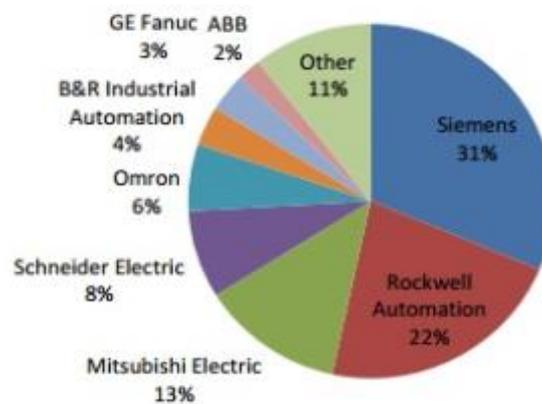
Figure 3: Europe's PLC market share [19].

Siemens dominates the PLC market in Europe whereas, North American market is ruled by Rockwell automation with their Allen Bradley range of PLCs.

1.1.2. PLC Programming:

The PLC accepts many different programming languages and such programming languages are chosen based on the level of implementation and users convenience. The different programming languages are:

- Ladder Diagram (LD)
- Functional Block Diagram (FBD)
- Sequential Function Charts (SFC)
- Structured Text (ST)
- Instruction List (IL)
- Extended Structured Text (ExSt)

These programming languages support standard IEC 61131-3 data types [2]. CODESYS supports all of the above programming languages. Ladder Logic Diagram and Functional Block Diagram are the most widely used programming methods in the PLC due to their simplicity and easy error diagnosis. In this thesis, the most common and easy Ladder Diagram is used as the programming tool. This programming language could be easily understood by anyone having little knowledge about PLC and automation.

1.1.2.1.   Ladder Diagram:

The ladder diagram resembles the structure of a ladder with two vertical rails and many rungs that could be used for programming. In the Ladder Diagram, the components should be inserted and connected to the vertical rails respectively since they represent the power supply. Left vertical line represents positive terminal and the right line represents the negative terminal. The process flow in the ladder diagram is from the left to right.
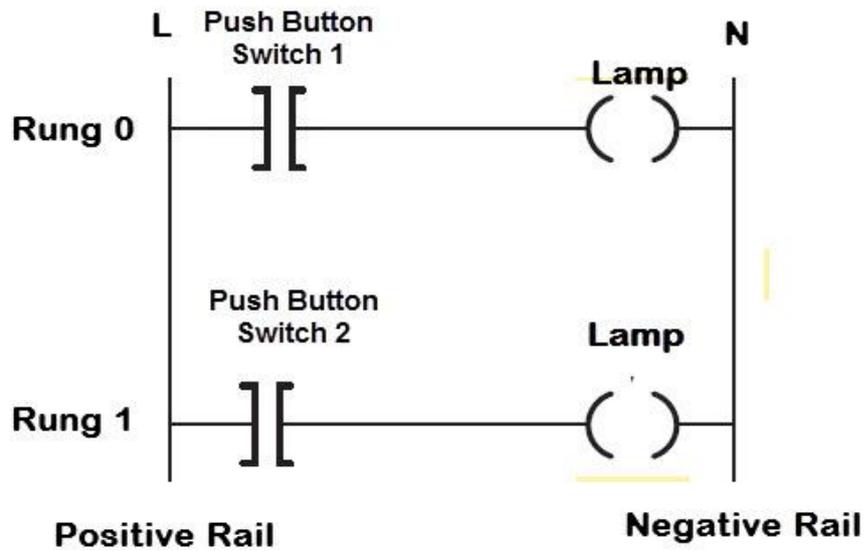
Figure 4: Basic ladder diagram [20].

1.1.2.2.   Functional Block Diagram:

A functional block diagram is also a graphical programming language oriented with IEC 61131-3 data types [3]. It works with a number of networks, where each network contains a logical and arithmetic expressions in their structure, calls of function blocks, a jump or a return instruction respectively.

Functional Boxes containing Boolean algebra are used here. Boxes and variables are connected by connecting lines. The signal is from left to right in the network. The signal flow in the editor runs from top to bottom, starting from network 1 [3].
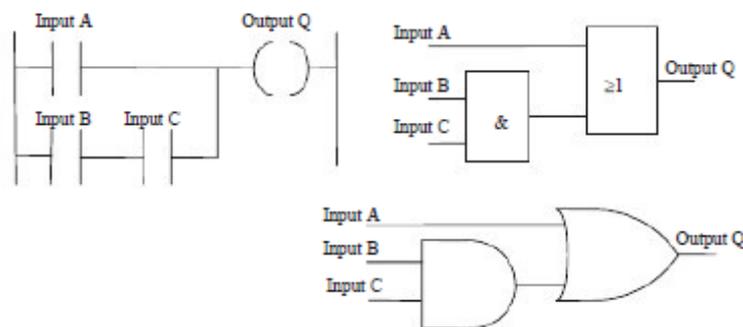
Ladder and functional block diagrams.

Figure 5: Basic Ladder Diagram and equivalent Functional Block Diagram [21].

Functional Block Diagram does a simple job of taking in the inputs and does the specified function it is intended to perform and gives the output. However in Ladder Diagram, the physical components perform the required functions.

1.1.2.3. Sequential Functional Chart (FSC):

The SFC method of programming is used when the system operation has to be described as a sequence of states or functions in the form of flow chart. The features of the SFC are:

- The operations are defined with individual sequentially connected states or steps that are represented by rectangular boxes, each having a particular state of control of the system.
- The connecting lines between the states has horizontal bar representing the transition condition that has to be satisfied before the system can change to one state to the another.
- When the transfer conditions are satisfied, the next step in SFC are executed in a program.
- The process continues from one step to the next until the cycle is completed.
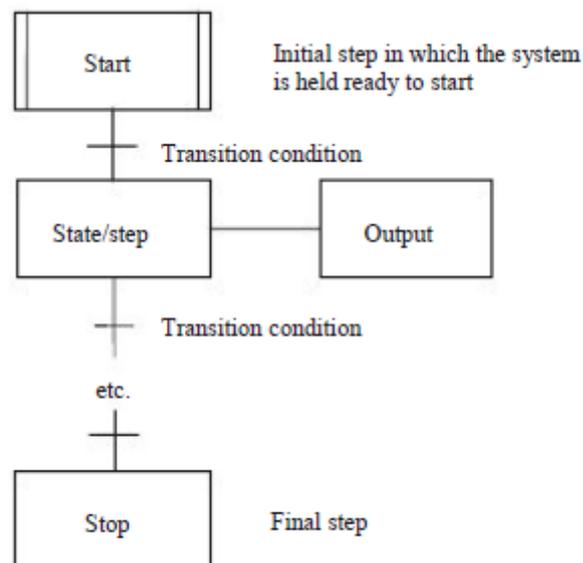
A state and its transition.

Figure 6: SFC program example [22].

1.1.2.4.   Structured Text:

The Structured Test is a programming language that is similar to C or Pascal. It is written with series of statements separated by semicolons which marks the end of line. The subroutines to call a well defined variable or change the variable from the library to cut short long programs. This makes this programming a unique and flexible to use. Many loops and conditional statements can also be used to make the programming much useful and simpler to use.
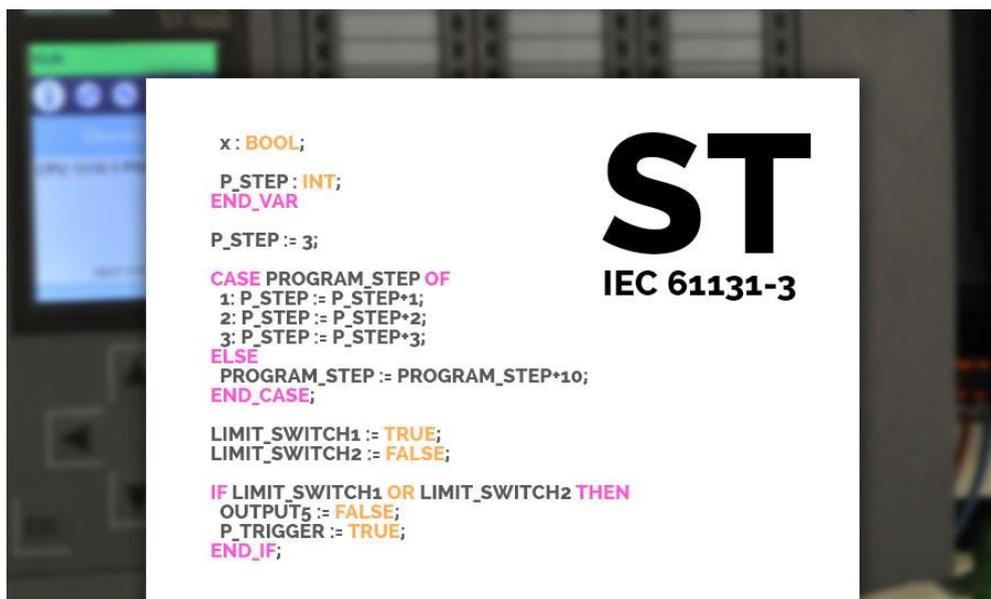
Figure 7: Structured Text example [23].

1.1.2.5.   Instruction List:

The instruction list programming is very similar to the Ladder Diagram, except the fact that it is written as simple codes instead of contacts. It uses text format to perform operations.
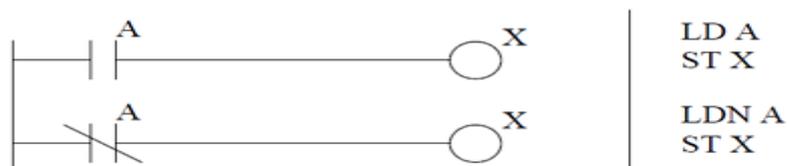
Figure 8: Instruction List example [24].

The above example shows the difference between the Ladder Diagram and its equivalent Instruction List programming. LD A refers to Load the value of A which in Ladder Diagram is a normally open contact A. LDN A refers normally closed contact. The command ST X defines to store the value of A into the X.

1.1.3. PLC Programming Device:

A PLC can be programmed using three different devices such as, Hand-Held PLC programmer, simply Display-Keyboard device and a personal computer. The figure 6 is a commonly used Hand-Held PLC programming device which displays only one line of programming code at a time. Only Boolean logic or a ladder logic could be used in the hand-held PLC programmer.

Figure 9: Hand-Held programming device [25].

The simple display-keyboard programming device consists of a display screen and a keyboard. This device is similar to a Human Machine Interface (HMI) which provides a visualization of the program.

Figure 10: HMI PLC Programming Device [26].

When it comes to manufacturing HMI PLC programming devices, Omron, Delta and Schneider electric stand out of the crowd with numerous products with different specifications to suite the end costumer needs. Personal computers or laptops can also be used for programming the PLCs but they require specific software's to perform such functions. Every PLC manufacturer has their own software's to program their own range of PLCs. CODESYS is a kind of PLC programming software which can work with most of he PLCs irrespective of the manufacturer.

1.1.4. Processor in PLC:

The PLC processor consist of three main components like any other microcontroller. They are as follows:

- Central Processor Unit (CPU)
- Arithmetic Logic Unit (ALU)
- Memory

The CPU is called the brain of the PLC which performs all the operations based on the command. It controls the Arithmetic Logic Unit to perform all the arithmetic and logical operations and uses the memory to store all the data and gives the output. The memory is usually of two types, ROM and RAM. For all the operations, the CPU uses only the RAM

memory due to its fetching speed. But the RAM memory is volatile in nature, which looses all the data it holds once the device turns off.
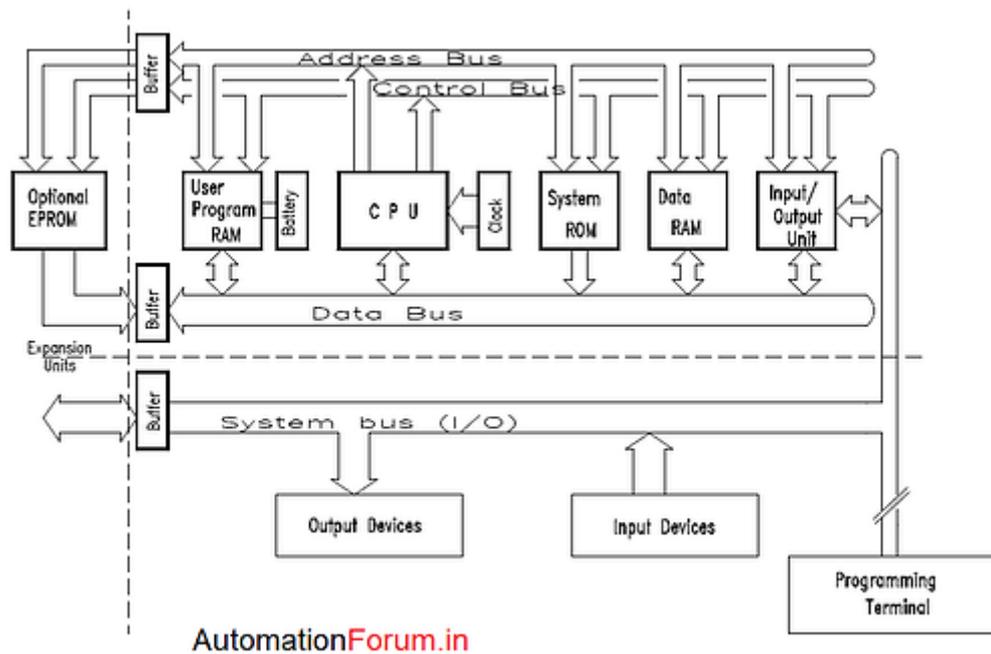
Figure 11: Block scheme of the PLC processor [27].

The functions of the CPU are:

- It receives input from various sensors, push buttons and switches.
- It executes the user written program.
- It performs arithmetic and logical decisions to control the operation of the equipment or process.
- It also performs data manipulation functions on the processes data and store them.
- It delivers respective output signals to various output control devices such as relay coils and solenoids which controls many equipments like motors, pumps, heaters and agitators.

CPU Operating Cycle

```
          ┌──────────────────────┐
          │     Start Scan       │◄─────┐
          └──────────┬───────────┘      │
                     ▼                   │
          ┌──────────────────────┐      │
          │   Internal checks    │      │
          └──────────┬───────────┘      │
                     ▼                   │
          ┌──────────────────────┐      │
          │     Scan Inputs      │      │
          └──────────┬───────────┘      │
                     ▼                   │
          ┌──────────────────────┐      │
          │ Execute Program Logic│      │
          └──────────┬───────────┘      │
                     ▼                   │
          ┌──────────────────────┐      │
          │    Update Outputs    │      │
          └──────────┬───────────┘      │
                     └──────────────────┘
```
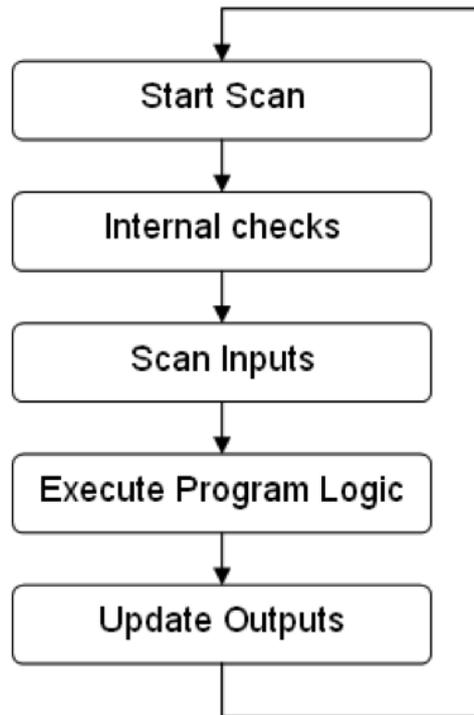
Figure 12: CPU operating cycle [28].

1.1.5. Advantages and Disadvantages of PLCs:

Advantages:

- Faster scan time.
- Extraordinary computational capabilities.
- A wide range of control application.
- Already mapped interfacing for the Inputs and Outputs.
- Simple and easy programming.
- Wide range of programming languages (LD, FBD, IL, ST).
- Supervisory controllability.
- Remote controlling.
- Small physical size.
- Flexibility in programming and reprogramming.
- Fast and easy troubleshooting.
- High speed counters in-built.
- High reliability.

Disadvantages:

- Fixed circuit operations.
- Limited to closed loop architecture.
- Extra modules are needed for expandability and flexibility
- Initial cost of implementation is high.

1.2. Input sensors to PLC:

Basically, Programmable Logic Controllers rely on various input sensors connected to their input terminal to get in the initial conditions of any given system controlled using PLC. Based on these sensors inputs, the PLC execute the program and does the necessary control operations to keep the system running.

The input to the PLC is scanned for every cycle and the change in the measured parameters from the sensors will be fed to the PLC. With the help of these input sensors, the PLC uses various control techniques to calculate the necessary control parameter values. The types of Input Sensors are:

1.2.1. Proximity Sensor:

The proximity sensors are used to detect the pressure or absence of objects using electromagnetic fields, sound and light. There are many types of proximity sensors, each suited to specific applications. The different types of proximity sensors are inductive, capacitive, ultrasonic and photoelectric sensors [13].

The capacitive sensors are most widely used proximity sensor as it can detect both metallic and non-metallic objects which are in the form of liquid, powder, solid and granulated. With their ability to sense through nonferrous materials, they are ideally used in glass manufacturing, liquid level detection and powder level detection. They usually have very short working range [13].

Proximity sensor comparison

Technology	Sensing range	Applications	Target materials
Inductive	<4-40 mm	Any close-range detection of ferrous material	Iron Steel Aluminum Copper etc.
Capacitative	<3-60 mm	Close-range detection of non-ferrous material	Liquids Wood Granulates Plastic Glass etc.
Photoelectric	<1mm- 60 mm	Long-range, smalll or large target detection	Silicon Plastic Paper Metal etc.
Ultrasonic	<30 mm- 3 mm	Long-range detection of targets with difficult surface properites. Color/reflectivity insensitive.	Cellophane Foam Glass Liquid Powder etc.

Figure 13: Comparison of the types of proximity sensors [29].

1.2.2. Mechanical Switches:

Mechanical switches are one of the most widely used form of input to the PLC. The PLC usually receives signal from the mechanical switch which is an ON/OFF signal. The switch has only two states, normally open and normally closed. Mechanical switches are used to detect the presence of any object or a workpiece. If there is a presence of an object, the mechanical switch is pressed and it becomes normally closed switch, thus sending an ON signal to the PLC. If there is no object present, the switch becomes normally open and the signal sent to the PLC is OFF [14].
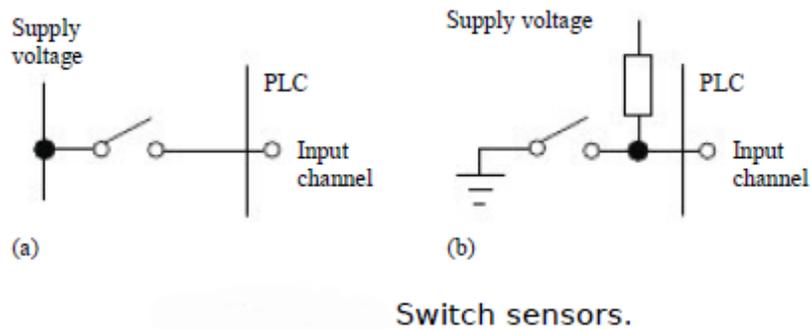
Switch sensors.

Figure 14: Example of switch sensor [30].

1.2.3. Temperature Sensors:

Temperature sensors are used to measure temperature of any given system in real-time and send the measured value of the temperature in the form of an analog signal to the PLC. The analog signal is then converted into digital form by the A/D converter in-built with the PLC. The digital signal is then used for processing and the PLC does the necessary control operations. This temperature measurement happens for every scan cycle of the PLC CPU.

There are many types of temperature sensors that could be coupled with PLC. The most basic temperature sensor is Bi-Metallic strip. It has two different metals connected or fused together. The two metals have different coefficients of expansion. When the strips are exposed to temperature, the one strip bends more than the other and this signalling the desired temperature level is reached. As the strip cools down, the bending is reversed and the strip comes back to its normal state [14].

The most commonly used temperature sensor with the PLC is the Resistive Temperature Detector (RTD). The resistance of the metals or the semiconductors changes with the temperature. The most commonly used metals for this purpose are platinum, nickel alloys and nickel. The resistance of the detector varies linearly with the respect to the temperature. The RTD's are stable, efficient and less expensive [14].
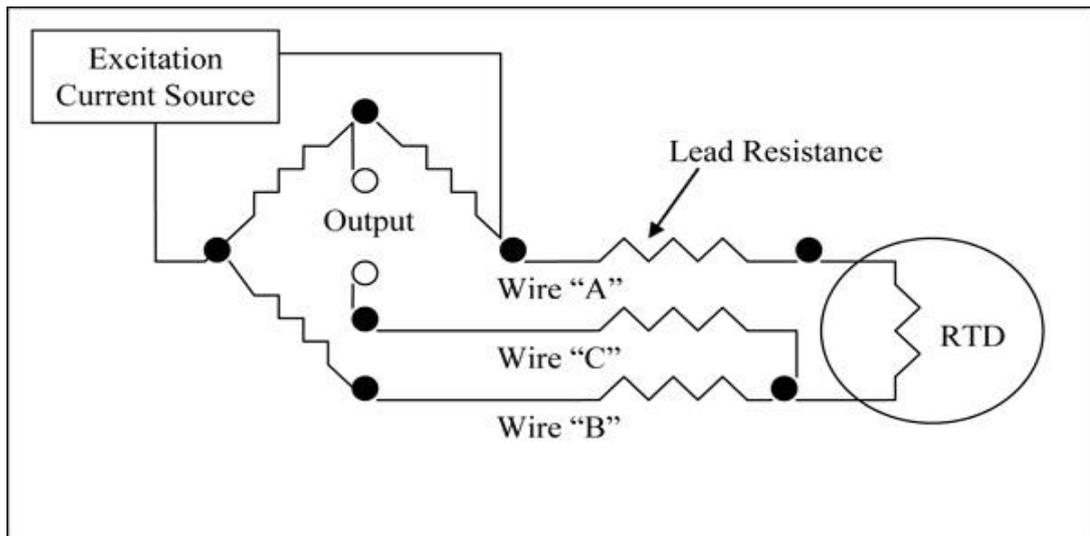
Figure 15: Sample RTD sensor [31].

1.2.4. Encoders:

An Encoder is a special type of sensor that senses or captures the position information and sends the data in digital form to the PLC. The position information can be analysed in many ways i.e. optically, magnetically and capacitive.

The two geometrics used in the encoders are linear and rotary. The linear encoder consists of a coded strip or a scale and a sensor head that reads the spacing between the coding to determine the position. The rotary type of the encoder consists of a coded wheel or a disc with a sensor head that detects the position. The optical rotary encoder is the most widely used encoders for the industrial application.
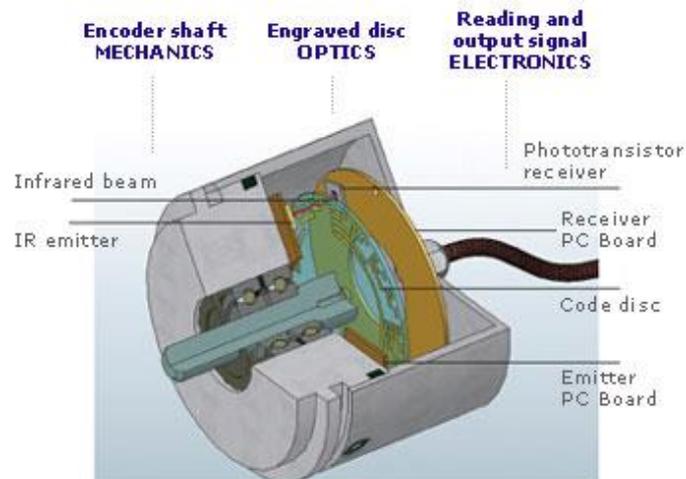
Figure 16: Optical Rotary Encoder [32].

1.2.5. Pressure Sensors:

The pressure sensor or a pressure transmitter is used to detect the change of pressure in any environment. It converts the pressure into an analog signal and transmits it to the PLC. The most commonly used pressure sensor is stain-gauge type of sensor. This type of sensor consists of a diaphragm i.e. a thin disc of metal or plastic. When there is a pressure change, the diaphragm deflects at the centre. This deflection is causing a push to the piezo electric crystal placed inside the setup. The strain gauge measures the difference through the change in the piezo crystal. The pressure is termed as absolute pressure when the pressure is measured in reference to the vacuum.
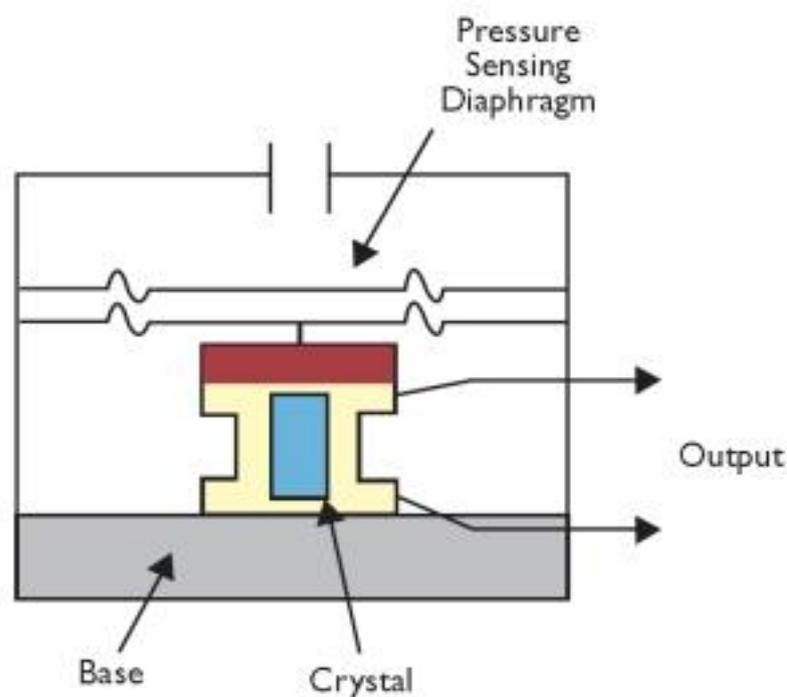
Figure 17: Pressure sensor with piezo electric crystal [33].

1.3. Output Actuators to PLC:

Actuators are used to convert electrical signal to mechanical movement. The electrical signal is here is the control signal from the PLC. Actuators translate output signal from the PLC into physical operations. They have coils that conduct the DC voltage to control switching.

1.3.1. Solenoids:

Solenoids are generally used for the control of flow of liquids and are also used as directional control valve. It uses Electro-Magnetic property to switch On and Off. Solenoids can also be called as Relays [15].

When the DC voltage from the PLC closes the switch of the solenoid, the current is passed through the coil and a strong magnetic field is created. This magnetic field attracts the ferromagnetic plunger towards it. This creates a switch i.e. the solenoid is closed. When the coil de-energizes, the plunger returns to its original position through spring action. Thus forming open and closed switch [15]. The solenoids are generally used in Hydraulic and Pneumatic systems which involves Flow of liquid and Air.
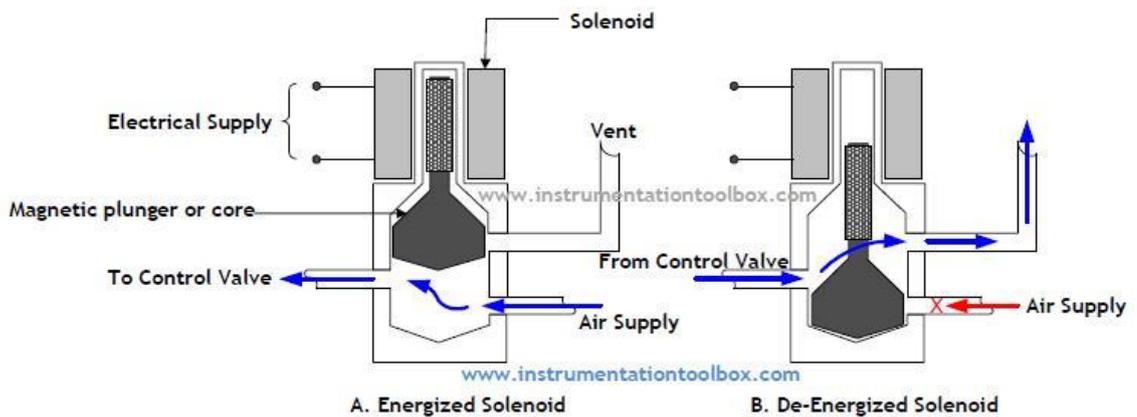
Figure 18: Working of Solenoids [34].

1.3.2. Motors:

Motors are used to convert electrical energy to mechanical energy using magnetic fields. They have magnitude of coils wound and mounted on to their frames [15]. There are three types of motors widely used with PLC devices. They are DC motor, Brushless DC motor, Stepper motor.

DC Motor has two major components, the Armature windings and the Field windings, when the voltage is applied to the field windings, a strong magnetic field is created and this magnetic field is encountered by the armature windings. The shafts start to rotate with speed directly proportional to the DC voltage. In basic PLC automation, the DC motor is controlled by a technique called Pulse Width Modulation (PWM). But in general, the PLC

controls the ON/OFF of the DC motor in most of the applications using Relays or Solenoids [15].
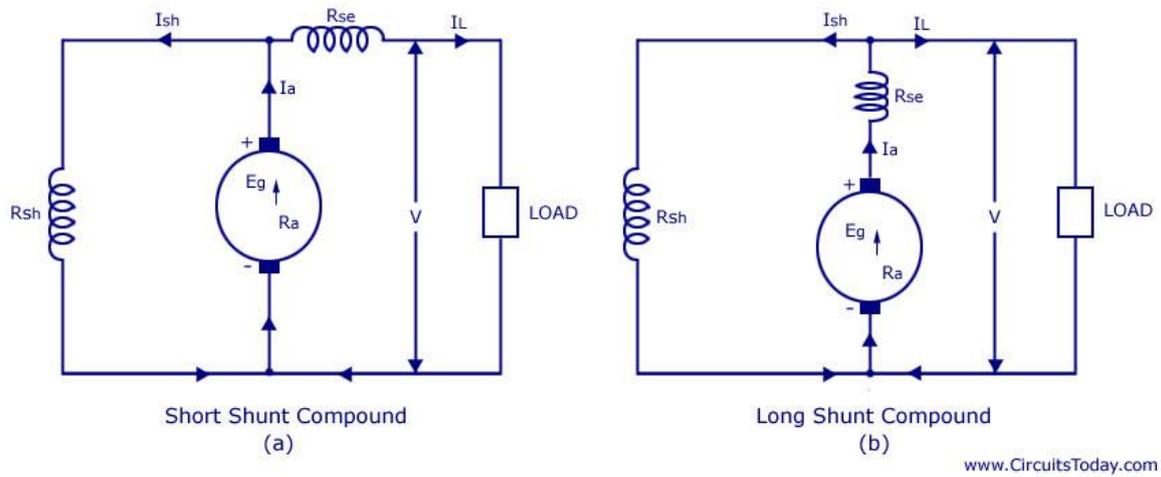
Figure 19: Different configurations of DC motor [35].

Stepper Motors are very different from the regular DC and AC motors in the fact that they cannot rotate continuously when the voltage is applied to their input terminals. The stepper motor is designed in such a way that, it rotates through equal angles called resolution. Each increment is called a Step. If one input pulse makes the motor rotate 60 degrees, it will take 6 such pulses to complete 360 degrees rotation [15]. Stepper motors are widely used in printers, 3D-printers, robots, machine tools, conveyer belts etc which requires exact positioning.
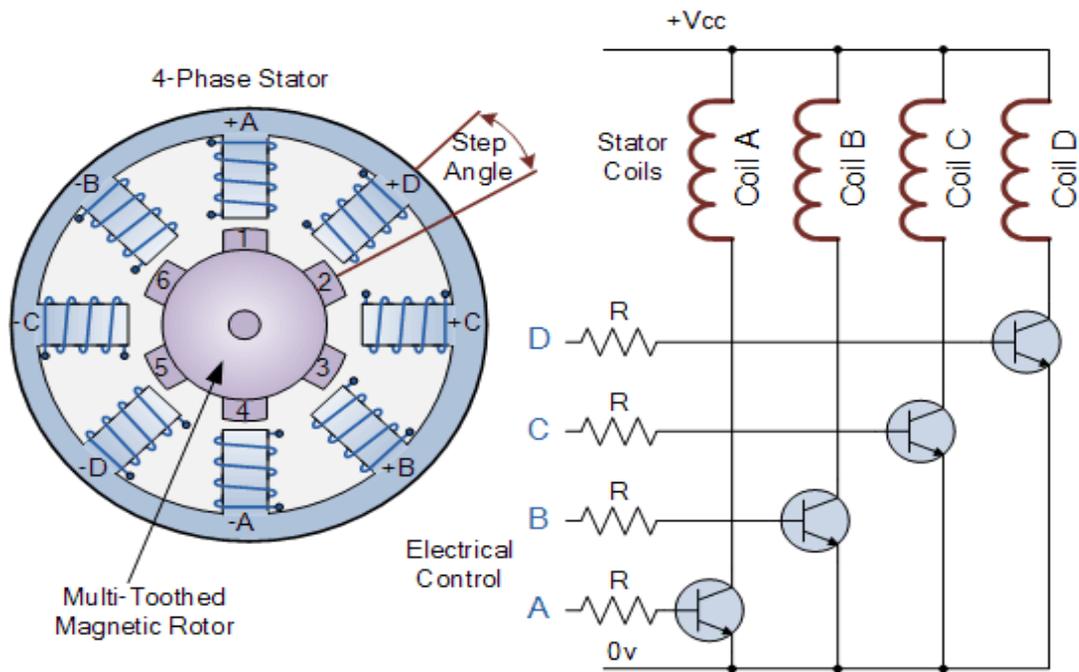
Figure 20: Stepper motor [36].

Brushless DC Motors are same like DC motors but they use Permanent magnets instead of using the current in the field winding to create a magnetic field. In this type of motor, the permanent magnet rotates with the coil. The control of the direction of rotation of the brushless DC motor is much easier than the control of regular DC motor. The wear and tear of Brushless DC motor is less than the DC motor with the fact that it doesn't have a brush like the regular one [15].
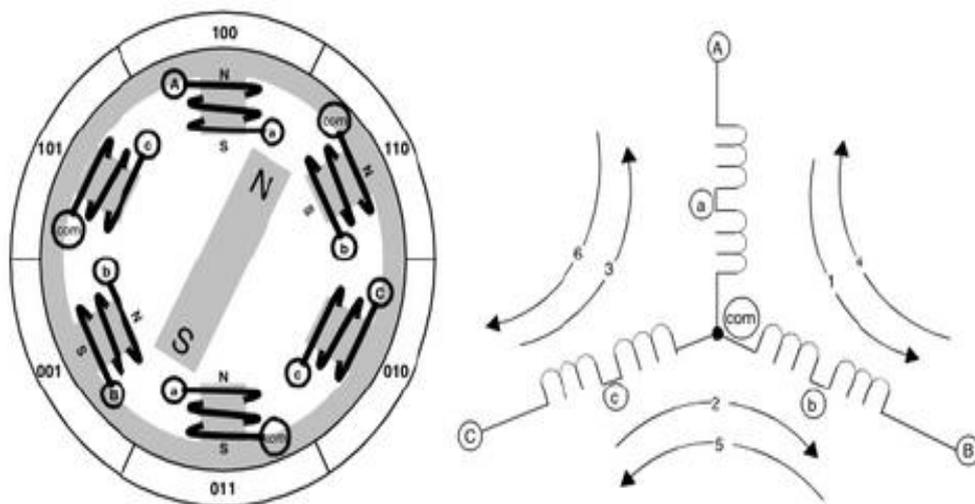
Figure 21: Brushless DC Motor [37].

1.3.3. Lights and Buzzers:

Pilot lights are always connected to the PLC automation systems. They are usually installed in the control system to signal the operator if the system is working fine. Usually green pilot lights are used to signal the system is working fine and red lights signal that something is wrong with the system and needs attention.

Buzzers on the other hand are always used as an alarm with sound, they can be used in PLC control system by varying the ON/OFF intervals. Buzzers are used for emergency signalling purpose. For example, when the temperature of the system has alarmingly exceeded the normal limit, the system sounds the buzzer to signal the situation to the operator. Pilot lights and buzzers are both very important part of the PLC control system.

Figure 22: Pilot lights [38].

Figure 23: Buzzers [39].

2. Literature Review:

In current industrial scenario, the PLC control systems is implemented in many applications such as manufacturing, waste water management, wind energy generation, air conditioning system and ventilating systems, chemical and petro-chemical industries. In all of the above sectors, the applications can be considered as a process control operation. As an example, in petro-chemical plant control system, the pumps and valves are controlled in real time with the help of input field data in real time as the process goes on. These kinds of control systems uses PID controller for the control operation.

PID controller decides the control valves from the previously stored data and comparing it with the current input and feedback valve from the output and sends the control signal valve to the PLC, thus controlling the control process in real time. These kind of systems are designed in such a way to adapt to any changes in the process and generates a control signal to control the process. In this section, some literature works are reviewed as follows:

Dilsad and Mustafa (2013) [4] for the purpose of training the engineering students on control process involving PID controllers, designed a level control system using PID control algorithm and implement it with the help of a PLC. Ladder diagram was designed in accordance with the PID control parameters. The level sensor and transmitter input was used for the feedback purpose. The above system was experimented and the results showed a working PID level control system.

Gang Zhao (2011) [5] did a survey on using Wireless Sensor Network in the industrial process control and monitoring, this survey has shown some compelling number of advantages and drawback of WSN as well. The advantages are reduced cost, better performance and easy maintenance and the drawbacks include limited memory, limited wireless network bandwidth, long processing time and high power consumption. Thus concluded the survey stating that the WSN approach is not a feasible option when it comes to industrial control and monitoring.

Da'na et al (2008) [6] designed a network platform for remote monitoring and controlling of PLCs. They used standard network protocols such as Transmission Control Protocol (TCP)/Internet Protocol (IP) and implemented in the Simatic S7 200 PLC system. The final goal was achieved as per the design.

Kondratenko et al (2015) [7] designed a PLC based system to control liquid level using Radar sensor remotely. The proposed system measured liquid level, temperature, volume and pressure of the liquid and controls them remotely. The system consist of PLC, Radar sensor, temperature sensor, point level sensors respectively. The PLC was programmed using Function Block Diagram (FBD) programming language. The design also had a Human Machine Interface (HMI) for easy monitoring of the operations. The final result was reliable as expected.

Panchal et al (2015) [8] designed a water tank level control using PI (Proportional Integral) controller in PLC and LabVIEW as SCADA. According to the authors, the system was designed for training purpose in order to understand the working of PLC based control system. The authors did some modelling of water tank, transducer modelling and control valve modelling. Panchal et al implemented the PI in PLC to test the system. The PI parameters were calculated using Ziegler Nicholas (Z-N) method. The experimental results were same as expected.

Raza et al (2011) [9] developed a PLC based PID control system of a heating tank. The authors also developed an HMI system for advanced control and monitoring purposes. the developed PID control maintained the temperature of the tank at a constant value and the operation was visualized with the help of the HMI system. The experimental results were as expected and the system worked fine.

Shaukat N (2002) [10] designed a PLC based liquid filling process. The base idea of the project was to design and develop a fully automated liquid filling and mixing system using the PLC. The designed system illustrated high level of autonomy for the filling and mixing process by avoiding unnecessary spilling and wasting of the liquid. Based on the experience, it was concluded that the PLC was a costly affair for the small industries but also stated that the extra cost is compensated by the performance and the reliability of the PLC.

Mallaradhya H. M (2013) [11] illustrated a PLC based liquid filling system that was able to fill the liquid in the bottled of different sizes. The system worked as per the expectations and the speed and efficiency of the liquid filling process was greatly improved by the use of the PLC based control system. SCADA system was used to monitor and control the process.

3. Applications of PLC:

PLCs are employed in almost every industrial sector which involves high level production requiring high reliability and efficiency. PLCs made automation of processes much easy and efficient due to its computational ability and simple hardware structure that requires less maintenance. PLCs are typical in certain industries for their production.

3.1. Automotive Industry:

Automotive industry was the first to use PLCs in their production plants to increase the production rate and the quantity of the products. Most of the production process were automated and required less manual attention, thus increasing the production rate. Mostly PLCs are implemented in the form of industrial robots that perform specific operations repetitively at faster speed. Those robots are employed foe welding of parts, painting, assembly line control, quality check and automatic gluing.
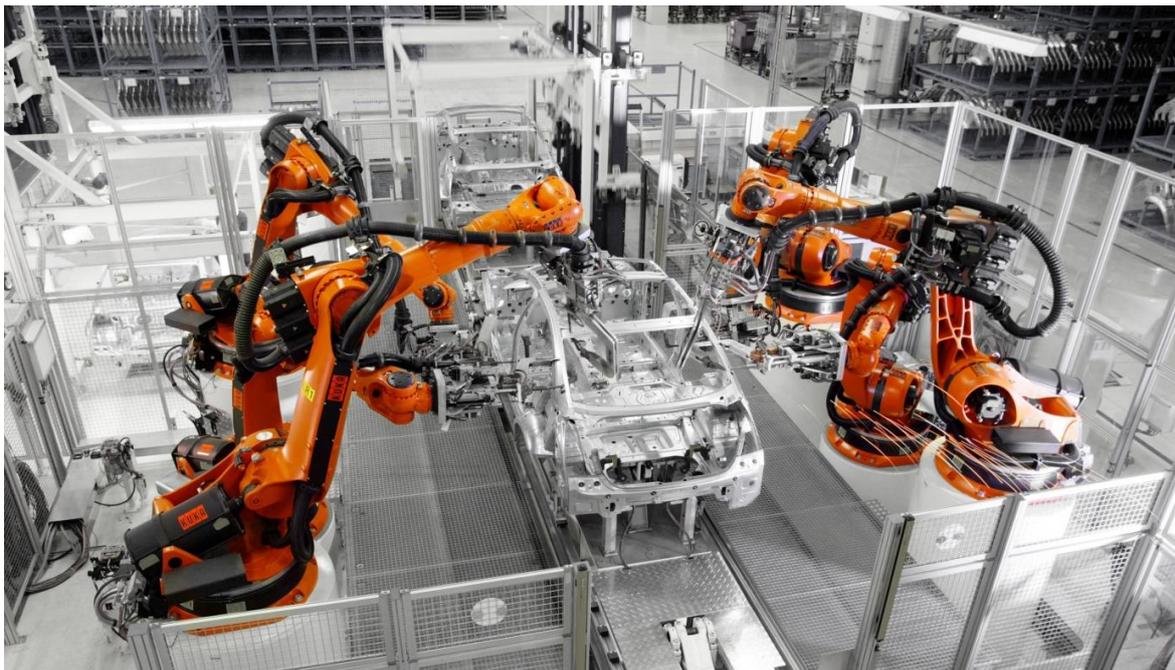
Figure 24: Automated industrial robots [40].

3.2. Chemical Industry:

Most chemical processes nowadays present hazards that have the adverse potential to affect people, assests and equipments and the environment. To overcome those disadvantages, PLCs have been used in the chemical industries for decades to automate the

chemical process control. The common processes that use automation in chemical industry is chemical filling, chemical batch missing, liquid heating and cooling, furnace control, pump control and valve etc. using PLCs improved the quality of the chemical products and increased the production rate and involved less human intervention.

Figure 25: Automatic chemical mixing equipment [41].

3.3. Glass Industry:

Since 1980s PLCs have been used in the glass industries for every process and the mainly to control material ratio, processing of the float glass, precision cutting of the processed glass. The PLCs are also used for storing data, digital quality control and position control of the glass cutting tool head etc.

Figure 26: Float glass cutting tool [42].

3.4. Beverage Industry:

The main application of PLC in beverage industry is for the automation of beverage mixer, bottle filling, conveyer control, storage level control, packaging etc. Automating the above processes increases the productivity, better handling, increased efficiency and eliminated wastage by spilling etc.

Figure 27: Conveyer system in beverage industry [43].

3.5.   Electronic Manufacturing:

In electronic manufacturing, the automation is used for assembly, fault testing, packing and dispensing. Using automated robots for assembly has increased the production rate and quality to much higher level. Robots mounted with Infrared (IR) cameras are used for fault testing and can predict possible premature failure of the assembled product. The process of soldering the connections is also automated.
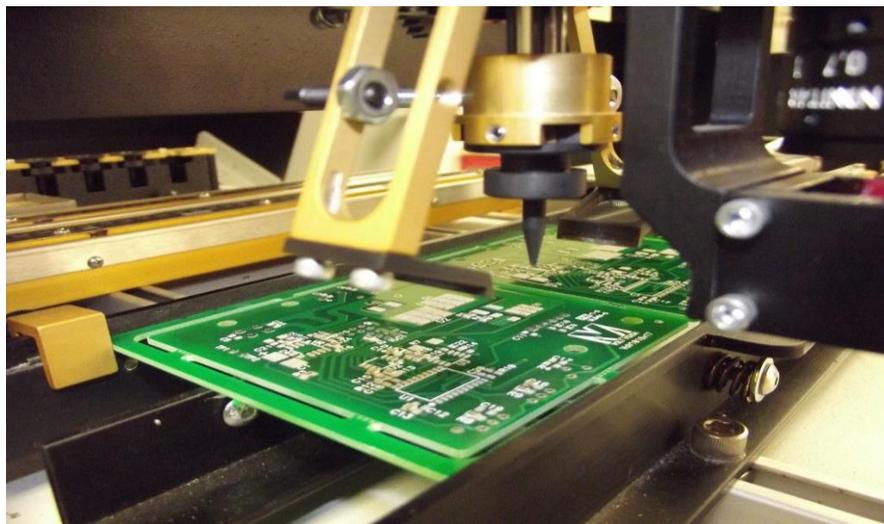
Figure 28: Electronics board assembly [49].

4. Proposed System:

The proposed system is an industrial chemical mixer that is controlled by the PLC. The mixing apparatus has many input sensors, output solenoid valves and actuators. The chemical mixing operation is simulated with the help of a PLC programming software called CODESYS by giving in respective inputs and analysing the working of the system in the simulation mode. The main objective of the PLC simulator is to read the input values and generate the required output signals based on the program logic.

4.1. Block schematic of the proposed system:

The block schematic gives the outline of the system components and their functional connection. Block scheme is used for the basic representation of the whole system. The functional block of the proposed system contains set of inputs in the form of sensors and push buttons. Those inputs are fed to the PLC and the PLC evaluates the program logic and devices the output. The outputs are the given to the set of output solenoid valves, actuators and pumps.
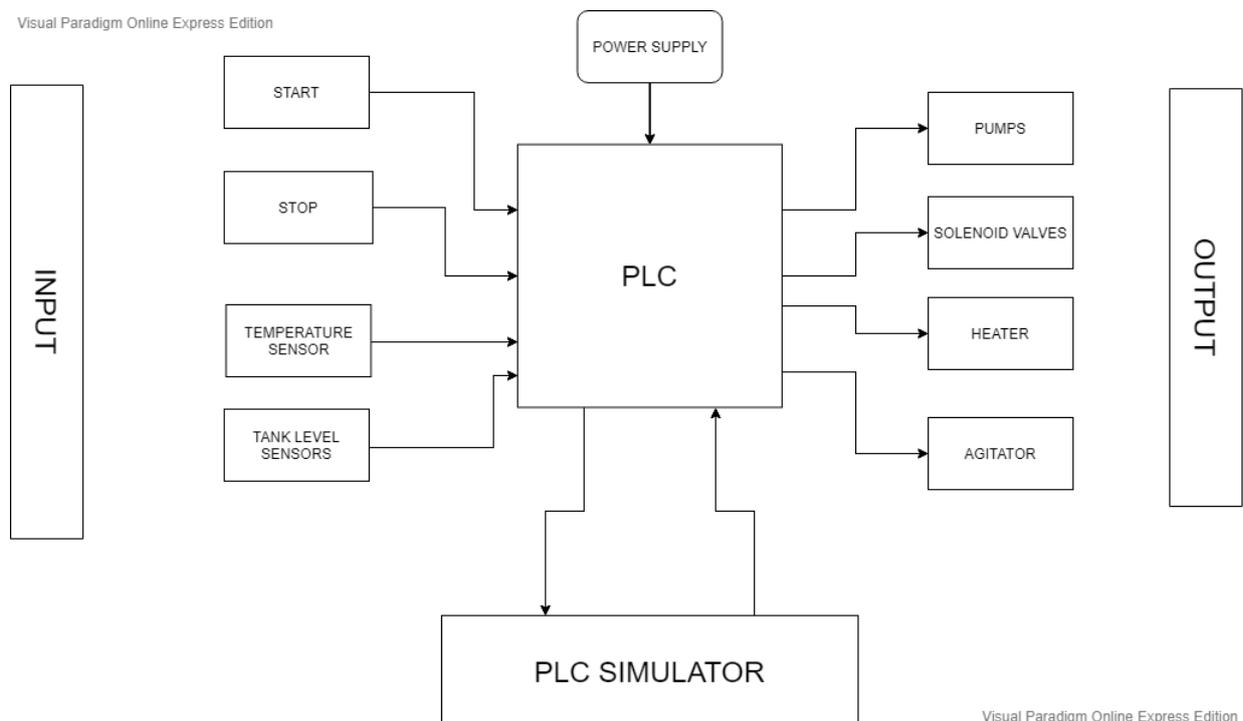
Figure 29: Block Scheme of the Proposed system.

From the above functional block of the system, it can be understood that the input module has two push buttons START and STOP. When START push button is pressed, the

operation is initialised and the PLC will evaluate all the input conditions and generates the output. When the STOP push button is pressed, all the operations are interrupted and stopped immediately. The temperature sensor is used to sense the temperature of the system in real time and update the PLC. The input from the temperature sensor is very crucial for the operation of the system. For the purpose of temperature sensing, thermocouples resistance temperature detectors (RTD) and thermistors can be used for temperature sensing.

The level indicator is a type of sensor that senses the level of liquid in the real time and it is given as input to the PLC. The level indicators can be of different types depending on their functionality i.e. discrete time level measurement or point level measurement and continuous time level measurement or precise level measurement.

The PLC is virtually implemented in the PLC SIMULATOR called CODESYS. It is a freeware program development environment used for programming the controller applications [12]. The standard version of the CODESYS can be used to program a PLC controller using programming languages such as Ladder Diagram (LD) and Functional Block Diagram (FBD) and has limited functions that could be used.

The output module of the system consists of pumps, solenoid valves, heater and an agitator. The pumps are used to pump the water to the respective tanks. The selection of pumps depends on the type of liquid and how much displacement is required. The pumps that are widely used in the chemical industries are centrifugal pump, positive displacement pumps and turbine pumps. Centrifugal pump is the most preferred one for pumping chemicals due to its large displacement capacity, high efficiency and simple design.

The solenoid valves are the most commonly used control element in any automated fluid systems. They perform simple operations like shut-off, release and distribute liquids. Solenoid valves are fast, highly reliable and offers safe switching between modes and long lifetime. They are widely used in chemical, petro-chemical, oil&gas industries where high level of automation is implemented. The solenoid valves are available in different types, linear action, Rocker actuator and plunger type actuator.

The output module also contains heater and agitator. The heater is a simple, electrically powered device which generates heat energy through its coil. The heater is turned ON/OFF when the temperature sensor detects a desired temperature level of the liquid. The

agitator is a mixing device that is electrically powered. It is used to mix two or more liquids uniformly. The agitator is turned ON/OFF when needed.

4.2. Schematic of the proposed system:

Schematic helps in visualising the overall system graphically. The schematic of the system shows three liquid tanks namely Tank 1, Tank 2 and Tank 3 respectively. The liquid is pumped into the tank 1 and tank 2 through pump 1 and pump 2. All the three tanks are equipped with level indicators to detect the Low and High levels of the liquids in each tank. Based on the levels, either Low or High, the level indicators sends in the input to the PLC.

The solenoid valves V1, V2 and V3 controls the out flow of liquid from tank 1, tank 2 and tank 3. They either shut-off or release the liquid out of the tanks. The tank 3 is equipped with a temperature sensor that senses the temperature of the liquid in the tank 3. This temperature sensor is used to trigger ON/OFF of the heater and the agitator.
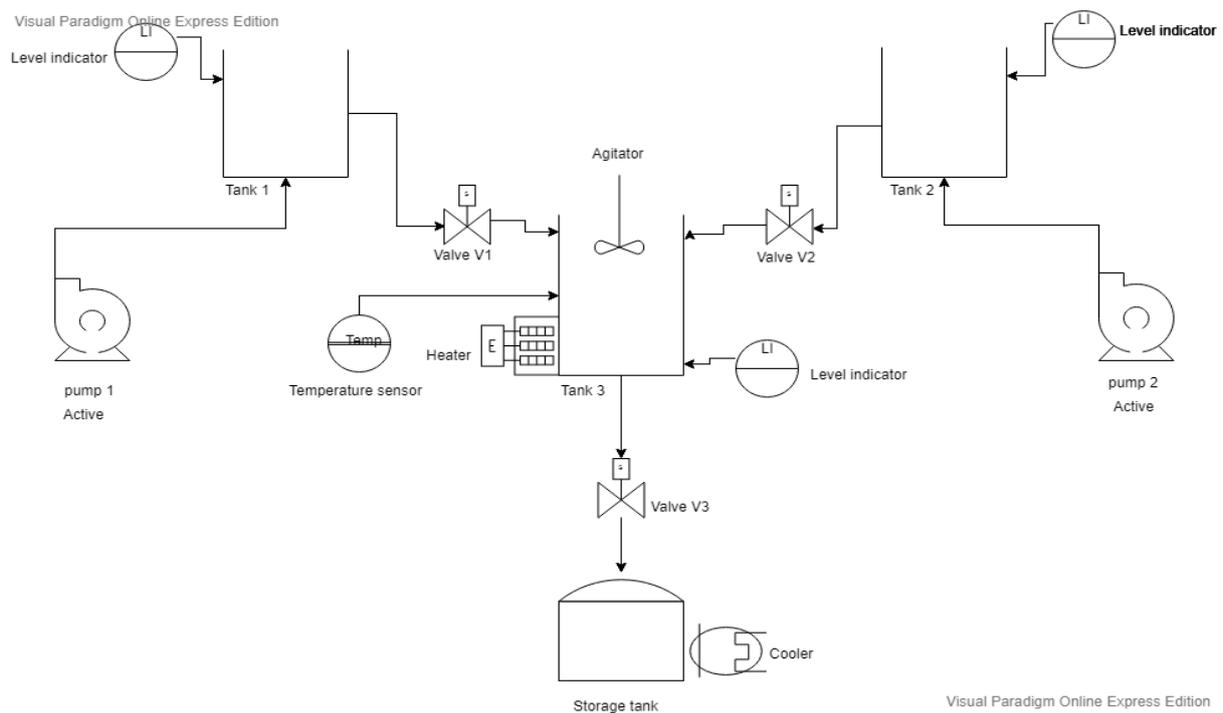
Figure 30: Schematic of the proposed system.

The storage tank is used to store the proposed liquid from tank 3 drained through the solenoid valve V3. The cooler is used to reduce the temperature of the processed liquid.

4.3. Algorithm:

1. Start the process.

2. Check for the L_Level of tank 1 and tank 2. If YES turn on Pump 1 and 2. If No check for the H_Level of tank 1 and tank 2.

3. The tank 1 and 2 gets filled.

4. When the tank gets filled H_Level is reached and the Pump 1 and 2 are turned off.

5. Valve 1 and Valve 2 are opened and allows the passage of liquids from tank 1 and tank 3 and tank 3.

6. When tank 1 and tank 2 reaches L_Level, the valves ae shut. The Heater and the agitator are turned ON. When the temperature of the liquid in tank 3 is greater than or equal to 40ºC, the agitator and heater are turned OFF.

7. Valve 3 is opened.

8. When tank 3 reaches L_Level the valve 3 is closed and the product is drained to the storage tank.

9. The process starts again from step 2.

10. Terminate the process.

The above algorithm explains the step to step process that takes place in the system. The PLC is programmed in such a way so as to follow the algorithm. The PLC operates by scanning the inputs for every cycle and generates the desired output.

The algorithm is further explained with the help of a process Flow Chart. It shows the technical flow of the program from START to STOP.

4.4. Flow Chart of the proposed system:
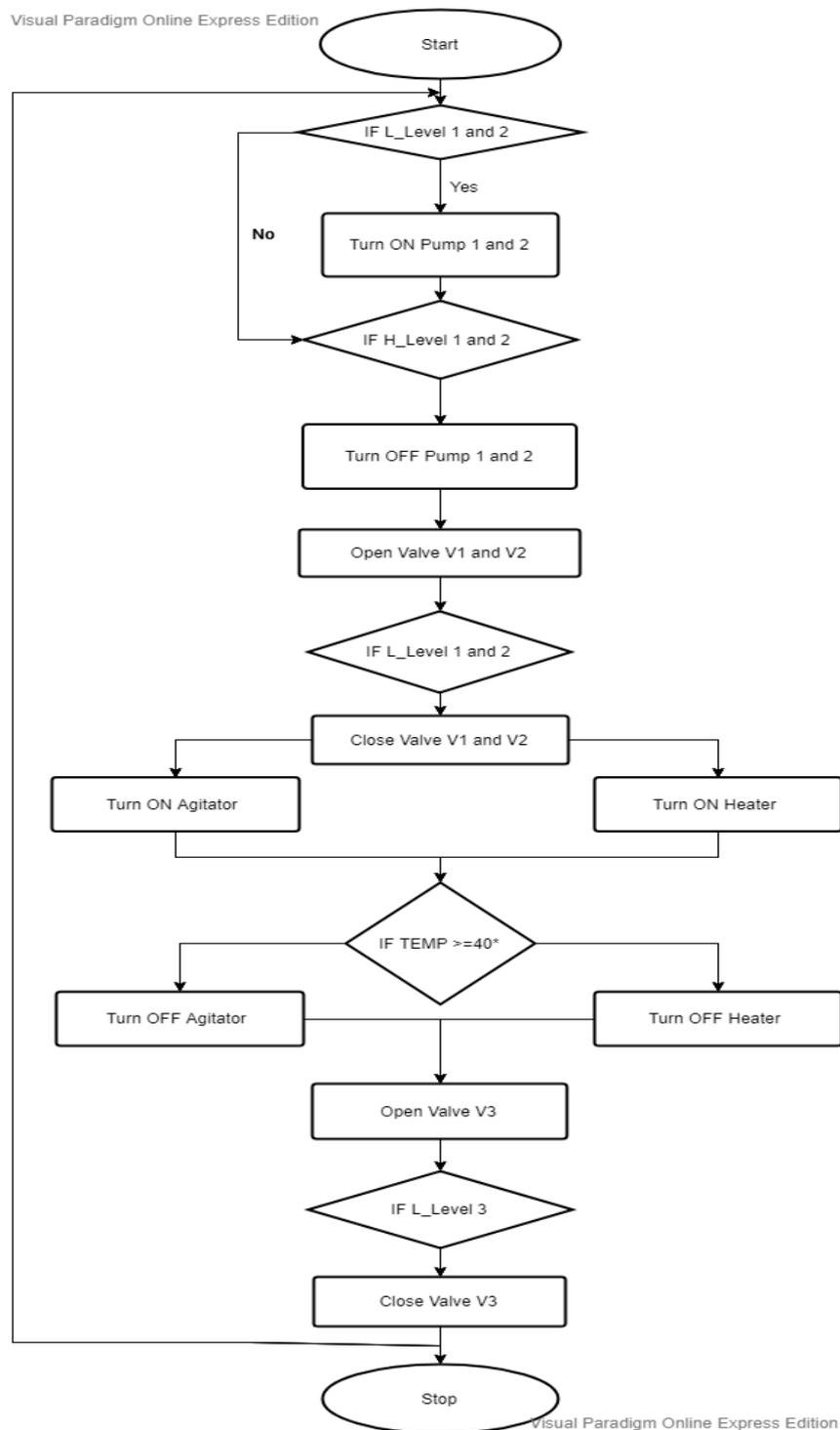
Figure 31: Flow chart of the proposed system.

The flow chart shows the flows of process from START to STOP. The initial condition of the program is to check for the L_Level of the tanks 1 & 2. If the condition is yes, the water PUMPS 1 &2 are started and the tanl 1&2 are filled. When the water level

reaches high level of the tanks i.e. H_Level of the tank 1 & 2 becomes TRUE, the PUMPS 1 & 2 are turned off.

When the PUMPS 1 & 2 are turned off, the solenoid valve V1 & V2 are actuated and the liquids are drained from tank 1 & 2 to the main mixing tank, tank 3. When tank 3 is filled and H_Level of tank 3 becomes TRUE, the solenoid valves V1 & V2 are shut-off, stopping the draining of liquids from the tanks 1 &2.

When tank 3 liquid level is high, i.e. when H_Levek becomes true, the AGITATOR and HEATER are turned ON. Now the temperature sensor starts to measure the temperature of the liquid in the tank 3, here we are using a reference temperature of 40 deg. So when the temperature of the liquid reaches the temperature >= 40 deg, the HEATER and AGITATOR are turned OFF and this actuates the solenoid valve V3 to release the liquid from tank 3 to the storage tank.

When the liquid level in the tank 3 reaches the low level, i.e. L_Level of tank 3 becomes TRUE, the solenoid valve V3 is shut-off. Then the process goes in loop starting from the initial conditions, i.ee. checking for the L_Level of the tanks 1 & 2. When the stop button is pressed, all the ongoing operations are stopped immediately.

4.5. Input sensors and output actuators for the system design:

The Ladder Diagram of the above defined system has number of Normally Open and Normally closed contacts or so called Relays, each having specified functions. The each Normally Open and Normally closed relays usually have two stated (open or close). In other words, they are Boolean in nature i.e. either 1 or 0 state.

The inputs to the systems are usually represented by Normally Open and Normally closed contacts and the outputs are represented by Coils. The input devices to the PLS are usually sensors and push buttons and the output devices are actuators which are generally solenoid valves and motors.

4.5.1. Input Sensors:

In our system design, there are many input sensors. In our design they are represented by Normally open and Normally closed switches.

The **Level indicator** that could be used for our system design should be of Boolean in nature i.e. it should give input as either 1 or 0. For this purpose we can use Ultrasonic level sensors. Ultrasonic level sensors are used to detect the presence of liquid about a certain level in a tank. It can give only precise information about the level of liquid present in the tank. If the liquid level is over the level sensor, it gives input to the PLC as "1". Boolean "1" refers to the presence of liquid at a certain level. Boolean "0" refers to no liquid is detected at this level. Ultrasonic sensors are called as point level detection sensor.

The **Temperature sensor** used for this system could be a thermistor temperature sensor. Thermistor sensors are widely used type of temperature sensor due to its simple working mechanism, inexpensiveness, interchangeable and can measure wide range of temperatures changes with high precision. Thermistors are made up of ceramic or polymer materials with heat sensing capabilities. The temperature measurement range of thermistors typically range from -90 deg C to 130 deg C. we can use a temperature transmitter to read the temperature from the thermistor and transmit it to the PLC. Using the measured temperature, the PLC compares it with reference temperature and does the e required operations.

Two pushbuttons, **START** and **STOP** are used to start and stop the process. All the operations are initialised only when the START button is pressed. STOP button is used as an emergency stop. When the STOP button is pressed, the whole operation is halted unless and until it is re-initiated.

4.5.2. Output Actuators:

The output actuators are responsible for carrying out the operation command given by the PLC. The actuators convert electrical energy into mechanical movements. Those mechanical movements are called actuations. In out design, all the output actuators are represented by output Coils.

The **Centrifugal Pumps** could be used for pumping liquids to the respective tanks in the above mentioned system design. Centrifugal pumps are highly reliable and easy to operate pumps. They can display large volume of liquids at higher rate compared to other types of pumps. They are mostly used for pumping low viscosity liquids and are suited only for low pressure pumping applications. They are widely used due to high reliability and low cost.

The **Solenoid Valves** are used for shutting off and releasing of the liquids from the tanks. They work on the principle of electromechanical switching. The type of solenoid valve that's suitable for our chemical mixing application is the plunger type of actuation. Solenoids provide high reliability, fast and safe switching, low control power requirement, low maintenance and compact design.

The **Heater** is used for heating the liquids or chemicals in the tank. They are also used for maintaining the temperature of the liquid in order to maintain the process parameters stable. There are many types of heaters available depending upon the working condition and amount of temperature to be generated. Process heaters or Over side heaters can be used for chemical mixing application. Both the heaters are used for closed loop applications.

The **Agitators** are used in process, pharmaceutical and cosmetic industries for the purpose of mixing two different liquids, to improve heat transfer, to move liquids to storage etc. They are usually a mechanical propeller or impeller that simply rotates at a required pace.

5. Design Implementation using CODESYS Software:

The above specified system design is implemented in a software platform to check if the design is working as desired. We use the CODESYS to design the PLC controller that helps to automate the chemical mixing process. The programming method that is used to design the controller is Ladder Diagram (LD). Ladder Diagram is used to program any sequential circuits or operations in the industrial control applications. It graphically represents the Relay Logic or circuit diagram. The program evaluate the connections between the contacts or logical checker and the actuators. **CODESYS (Controller Development System)** is a development environment for programming controller applications according to the international industrial standard IEC 61131-3 [2].

In the Ladder Diagram of the above mentioned chemical mixing system, many number of Normally Open (NO) and Normally Closed (NC) switches are used. Those switches are switched open and close based on the inputs from the input sensors. The purposed of the PLC in the system is to Turn ON/OFF the two pumps that are connected to the tanks 1 & 2 based on the input from the Level Indicating sensors places in the respective tanks. Then the PLC also actuates the output solenoid valves to discharge the liquids.

5.1. The complete Ladder Diagram of the system designed using CODESYS:

```
1      PROGRAM  PLC_PRG
2
3      VAR
4          SR_0 :  SR ;
5          START :  BOOL ;
6          L_LEVEL1 :  BOOL ;
7          L_LEVEL2 :  BOOL ;
8          H_LEVEL1 :  BOOL ;
9          H_LEVEL2 :  BOOL ;
10         STOP :  BOOL ;
11         PUMP_1 :  BOOL ;
12         PUMP_2 :  BOOL ;
13         SR_1 :  SR ;
14         SOL_VALVE1 :  BOOL ;
15         SOL_VALVE2 :  BOOL ;
16         SR_2 :  SR ;
17         H_LEVEL3 :  BOOL ;
18         AGITATOR :  BOOL ;
19         HEATER :  BOOL ;
20
21
22         SR_3 :  SR ;
23         SOL_VALVE3 :  BOOL ;
24         L_LEVEL_3 :  BOOL ;
25     END_VAR
26
```

2

| H_LEVEL1 | H_LEVEL2 | SR_1 | SOL_VALVE1 |
| — | — | — | — |

```
    H_LEVEL1      H_LEVEL2              SR_1                        SOL_VALVE1
  ───┤ ├──────────┤ ├──────┐       ┌──────SR──────┐         ┌──────(S)
                           │       SET1        Q1 │─────────┤    SOL_VALVE2
    SOL_VALVE1    SOL_VALVE2         │              │         └──────(S)
  ───┤/├──────────┤/├──────┤       │              │
                           │       │              │
    L_LEVEL1      L_LEVEL2  │       │              │
  ───┤ ├──────────┤ ├───────┤      RESET          │
                           │       └──────────────┘
        STOP                │
  ───────┤ ├────────────────┘
```

3

4

```
    H_LEVEL3                          SR_2                         AGITATOR
  ───┤ ├──────────────┐        ┌──────SR──────┐               ┌──────( )
                      │        SET1        Q1 │───────────────┤    HEATER
            GE         │        │              │               └──────( )
        ┌──EN  ≥──┐    │        │              │
     60─┤         ├────┤       RESET          │
     40─┤         │    │        └──────────────┘
        └─────────┘    │
        STOP           │
  ───────┤ ├───────────┘
```

5

6

```
            GE                         SR_3                       SOL_VALVE3
        ┌──EN  ≥──┐         ┌──────SR──────┐               ┌──────(S)
     60─┤         ├─────────SET1        Q1 │───────────────┘
     40─┤         │         │              │
        └─────────┘         │              │
    SOL_VALVE3              │              │
  ───┤/├───────────────────┤              │
                           │              │
    L_LEVEL_3              │              │
  ───┤ ├──────────────────RESET          │
                           └──────────────┘
        STOP
  ───────┤ ├────────────────
```

```
7     L_LEVEL_3        START
         ─┤ ├─          ─┤ ├─
```
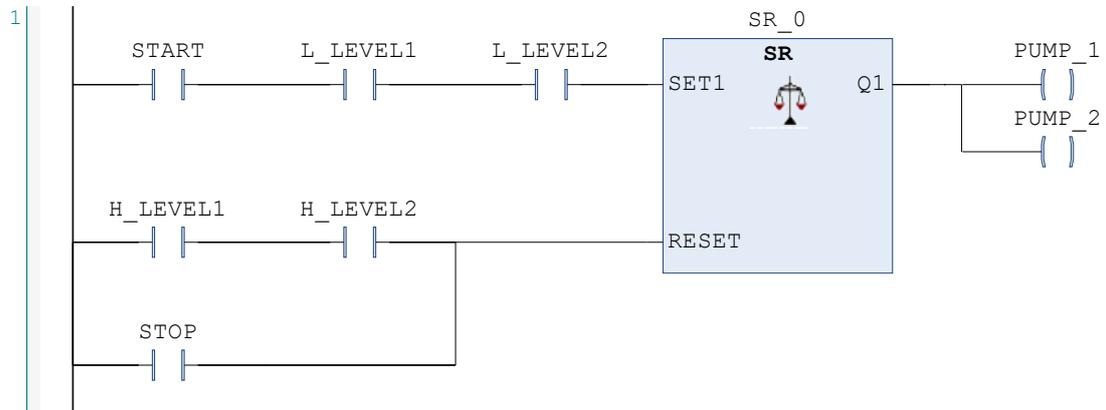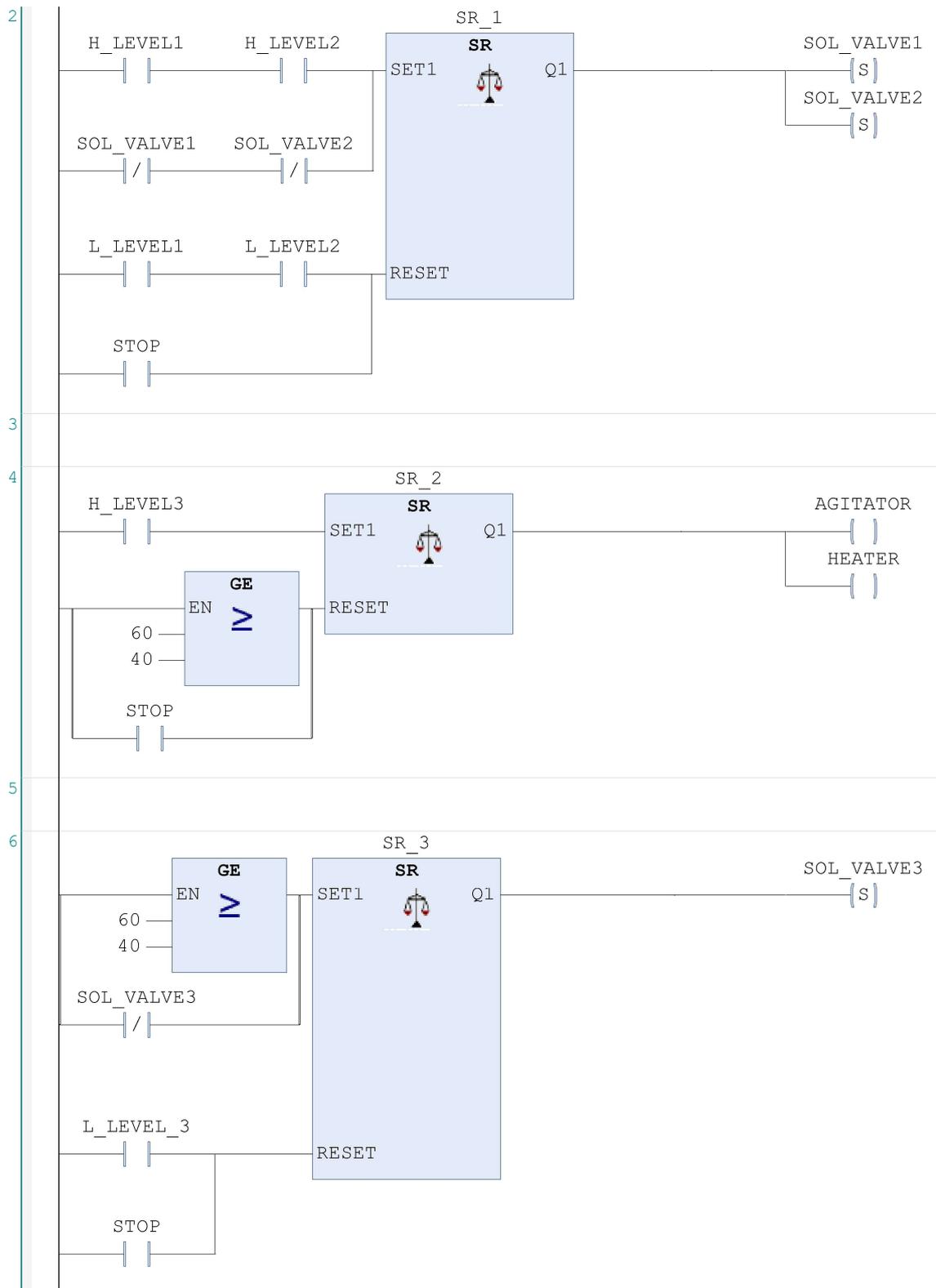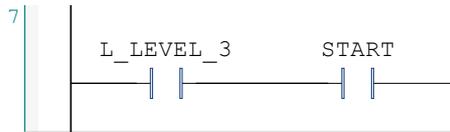
5.2. System Components and Explanation:

No	Components	Explanation
1	START	System ready and inputs are received from the input sensors.
2	STOP	Emergency stop
3	L_LEVEL1 L_LEVEL2 L_LEVEL3	Low Level indication sensor in tank 1, tank 2 and tank 3 respectively.
4	H_LEVEL1 H_LEVEL2 H_LEVEL3	High Level indication sensor in tank 1, tank 2 and tank 3 respectively.
5	PUMP1 PUMP2	To fill the liquids in tank 1 and tank2.
6	SOL_VALVE1 SOL_VALVE2 SOL_VALVE3	Shut off/ Release operation. Used for discharging of liquids from tank 1, tank 2 and tank 3 respectively.
7	AGITATOR	Used for mixing liquids in tank 3.
8	HEATER	Used for heating liquid in tank 3.
9	TEMPERATURE SENSOR	Measures the temperature of the liquid in tank 3.

Table 1: System components and explanation using CODESYS.

5.3. System Components and their Data Types:

NO	Components	Data type
1	START	BOOL (TRUE OR FALSE)
2	STOP	BOOL (TRUE OR FALSE)
3	L_LEVEL1 L_LEVEL2 L_LEVEL3	BOOL (TRUE OR FALSE)
4	H_LEVEL1 H_LEVEL2 H_LEVEL3	BOOL (TRUE OR FALSE)
5	PUMP_1 PUMP_2	BOOL (TRUE OR FALSE)
6	SOL_VALVE1 SOL_VALVE2	BOOL (TRUE OR FALSE)
7	SR_0 SR_1 SR_2 SR_3	SET DOMINANT BI-STABLE LATCH - BOOL (TRUE OR FALSE)
8	AGITATOR	BOOL (TRUE OR FALSE)
9	HEATER	BOOL (TRUE OR FALSE)
10	COMPARATOR (GE)	**Input** - INTEGER (INT) NUMERICAL VALUE **Output**–BOOLEAN (BOOL) (TRUE OR FALSE)

Table 2: System components and their Data Types using CODESYS.

5.4. Ladder Diagram Working:

Initially, all the Inputs to the PLC are Null and the PLC is at the stand-by condition. The whole system is powered only when the START pushbutton is pressed. When the START pushbutton is pressed, the system is set to ready condition and starts receiving input data from the input sensors.

The total input sensors in the system comprises of three sets of Level Indication sensors and a Temperature sensor. Level indication sensors are used to detect the water level in the tanks. They can only detect if the water level in the tank is either HIGH or LOW, since those level sensors are Point detection sensors i.e. they are Boolean in nature. The temperature sensor measures the temperature of the liquid in the tank 3 and feeds the temperature data as an input to the PLC.

The initial starting condition of the process is to check for the LOW LEVEL sensor indication in tank 1 and tank 2 (L_Level 1 & L_Level 2). If the condition is TRUE, the PLC turns ON the two PUMPS, pump 1 and pump2 respectively and the liquids are filled in the tanks.
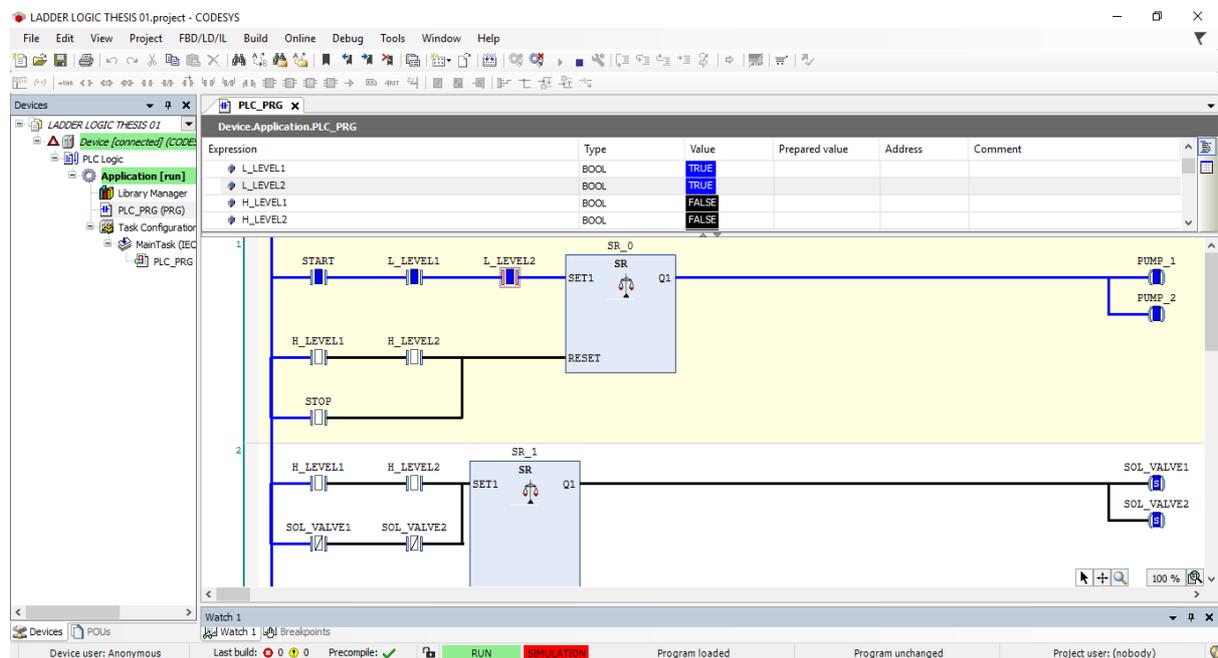
Figure 32: CODESYS Ladder Programming screenshot.

The figure 2, shows that when the condition of the LOW level sensors of tank 1 and tank 2 are TRUE, the Pump 1 and Pump 2 are activated. When the tank 1 and tank 2 are filled, the LOW Level sensor condition becomes FALSE but, still the pumps 1 and 2 are in set condition.
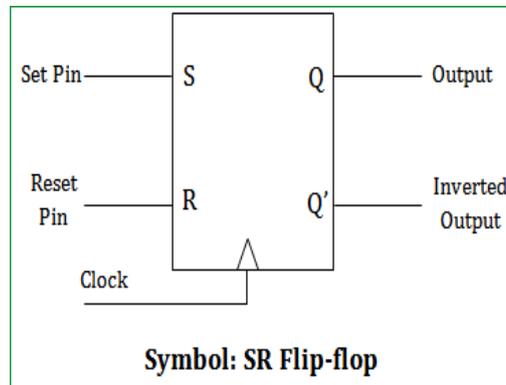
Figure 33: SR Flip Flop [44].

Inputs		Outputs		Action
S	R	Q	Q'	
0	0	Q_n	Q'_n	No change
0	1	0	1	Reset
1	0	1	0	Set
1	1	0	0	Undefined

Figure 34: SR Flip Flop state table [45].

We are using a Bi-stable functional block to control the Pumps, the widely known **SR (Set Reset) Flip Flops.** SR is the so called Bi-stable functional block. The state Q1 of the SR flip flop depends on the SET and RESET condition. When the SET condition is TRUE, the state Q1 activates the Pumps. The Pumps are in SET state even if the SET conditions are FALSE. When the RESET conditions are TRUE, the state Q1 is RESET and the Pumps are turned OFF. The RESET condition is HIGH Level indication to be TRUE. If the liquid level in tank 1 and 2 are HIGH, the pumps 1 and 2 should be turned OFF.
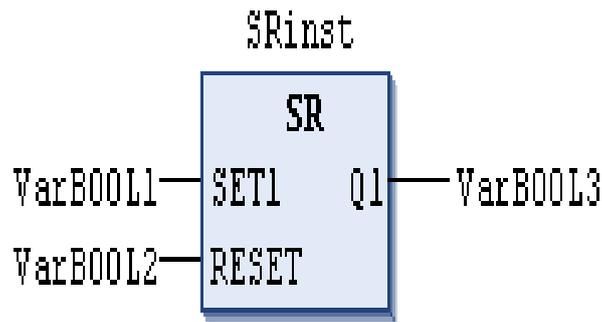
Figure 35: SR Flip Flop from CODESYS programming software [46].
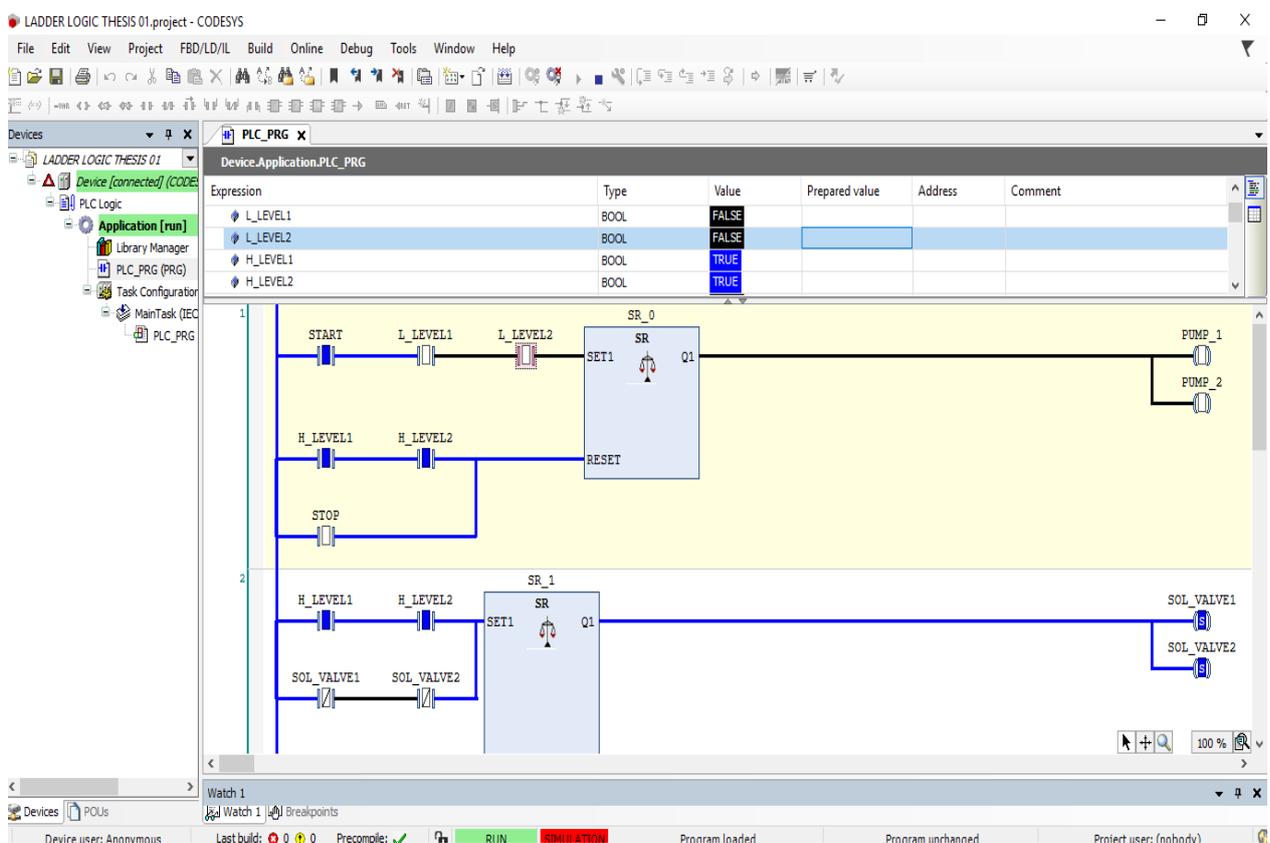
Figure 36: Codesys Ladder Programming screenshot.

From the figure 33, it can be seen that when the HIGH Level indication sensors are in TRUE condition, the Pumps are turned OFF. At the same time, the condition to OPEN the Solenoid Valves 1 and 2 are the HIGH Level indication sensors of tank 1 and 2 to be TRUE. Thus a single set of input conditions can be used to trigger SET & RESET of one or more operations.

When the tank 1 and 2 are full, the HIGH Level indication becomes TRUE and this triggers the Solenoid Valves of tank 1 and 2 to OPEN (Release). When the valves are opened, the liquids from the tank 1 and 2 are discharged to the tank 3. Now, when the liquid level of the tank 1 and 2 becomes low, the LOW level indication sensor becomes TRUE, this condition can be used to RESET the Solenoid valves to CLOSE (Shut-Off) condition.

The above operation completes one operating cycle for the two pumps 1 & 2 and for the two solenoids valves 1 & 2. When the two solenoid valves are shut-off, whole new set of operations are triggered in the system i.e. the main purpose of the system, chemical mixing operation.
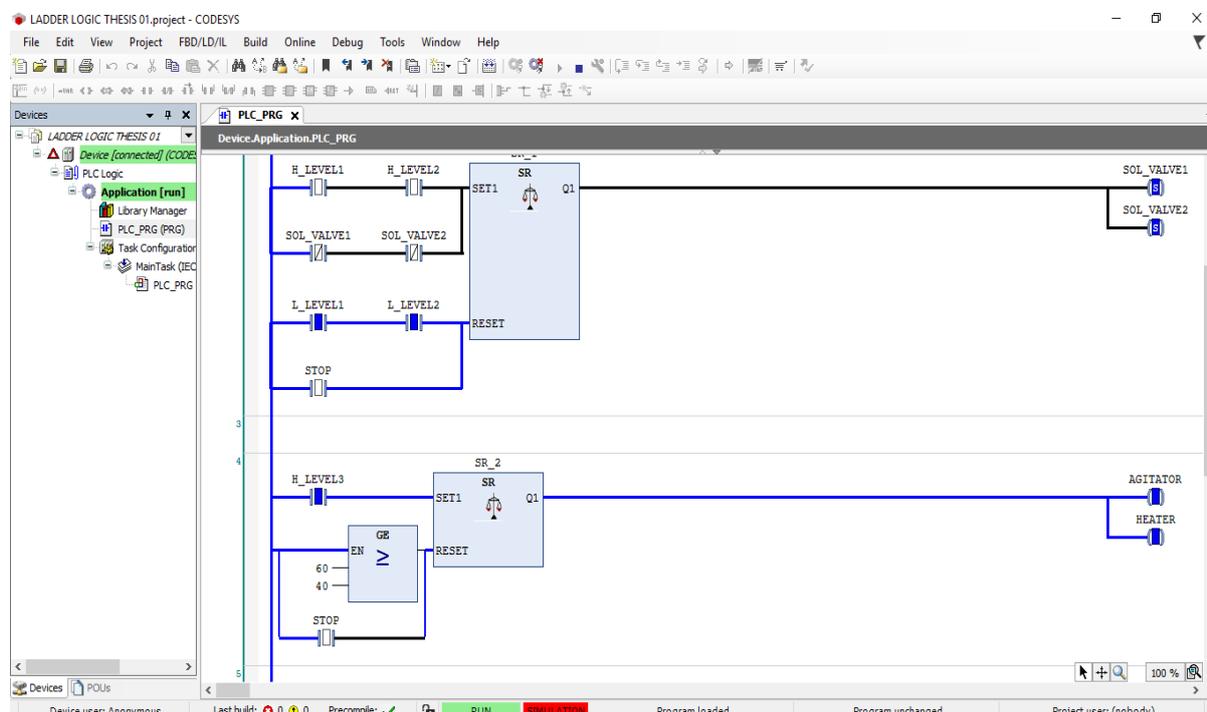
Figure 37: CODESYS Ladder programming screenshot.

From figure 36, it can be seen that the LOW level indication of the tank 1 & 2 have Shut-off of the two solenoid valves 1 & 2.

When the liquid level of the tank 3 is HIGH, i.e. HIGH_Level 3 is TRUE, the AGITATOR and the HEATER in the tank 3 are activated. The AGITATOR mixes the liquid in the tank uniformly and the HEATER is used for heating the liquid and maintaining the temperature of the liquid at a desired temperature.

The Temperature sensor connected to the tank 3 measures the temperature in real-time. In our system, the temperature reference point for the liquid in tank 3 is set at 40 deg C. The PLC is programmed in such a way that if the temperature of the liquid in tank 3 is greater than or equal to 40 deg C (TEMP>= 40 deg C), the PLC will turn off the Agitator and the Heater.

The temperature control in the above system is programmed using a **Greater than or Equal to Comparator (GE)** in the Ladder Diagram. The function of the GE comparator is to compare the two input values and if the Greater than or Equal to condition is satisfied, then the output is triggered.
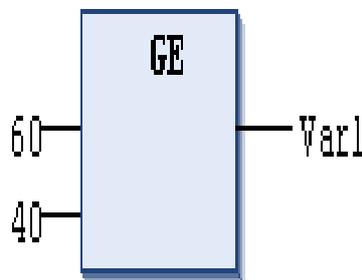
Figure 38: Greater than or Equal to comparator block [47].

The comparator has the reference value of the temperature as 40 deg C. The reference input is considered as the Source input 2. The source input 1 is from the reading of the temperature sensor. The PLC compares the two values and decides the output. When S1>=S2, the condition is TRUE and the output trigger is received from the comparator.

The output of the comparator is used as the RESET signal for the SR flip flop **SR_2.** When the comparator output is TRUE, the Agitator and the Heater are turned off by the RESERT condition.
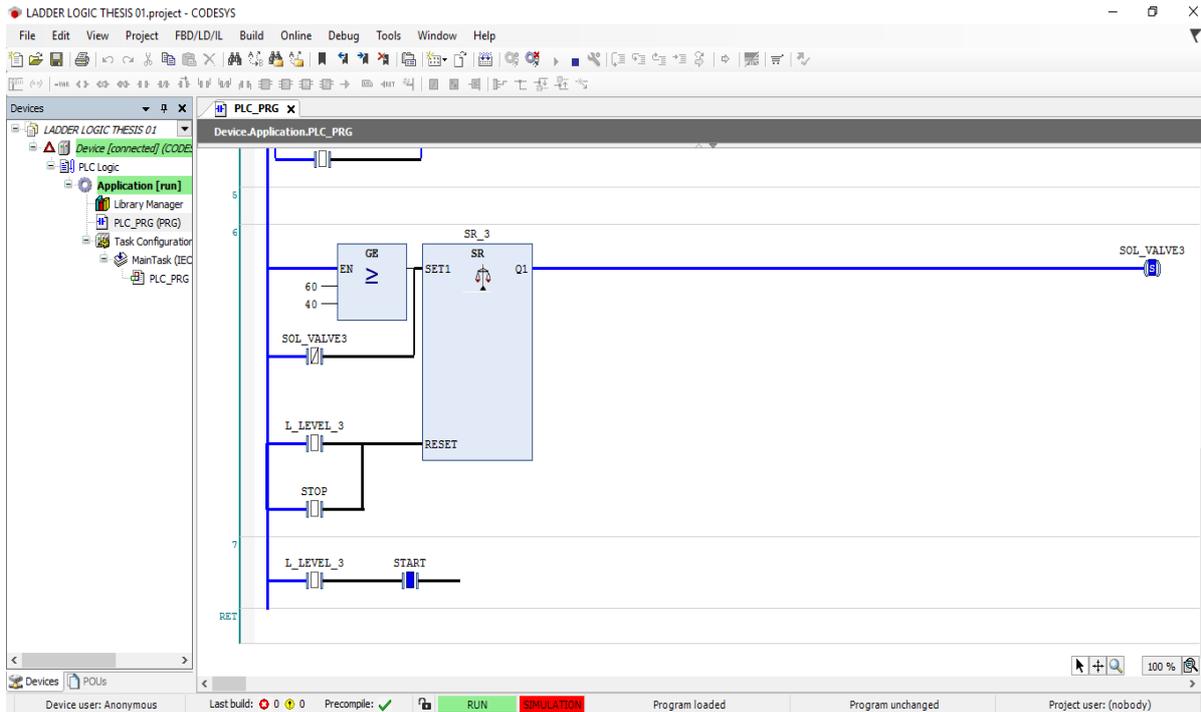
Figure 39: CODESYS Ladder programming screenshot.

Figure 38, shows that the TRUE output of the GE comparator block that is used to control the Agitator and the Heater to be Turned ON/OFF is also used to trigger the Solenoid valve of tank 3.

The SET condition to Release (OPEN) the Solenoid valve 3 (SOL_VALVE3) is the output trigger from the GE comparator. If the output from the GE comparator is TRUE, then SR flip flop **SR_3** will be in SET condition i.e. Solenoid valve 3 is actuated and the liquid is discharged from tank 3. The SR_3 will be in SET state until the RESET condition is triggered.

When the liquid is completely discharged from tank 3 to the storage tank as per the design, the LOW Level indication (L_Level_3) of the tank is activated. This LOW Level indication (L_Level_3) is used as the RESET condition for the SR_3 flip flop. Therefore, when L_Level_3 is TRUE, the RESET condition is satisfied and the Solenoid valve of tank 3 (SOL_Valves) is shut-off. This step marks the completion of one operating cycle of the whole system.
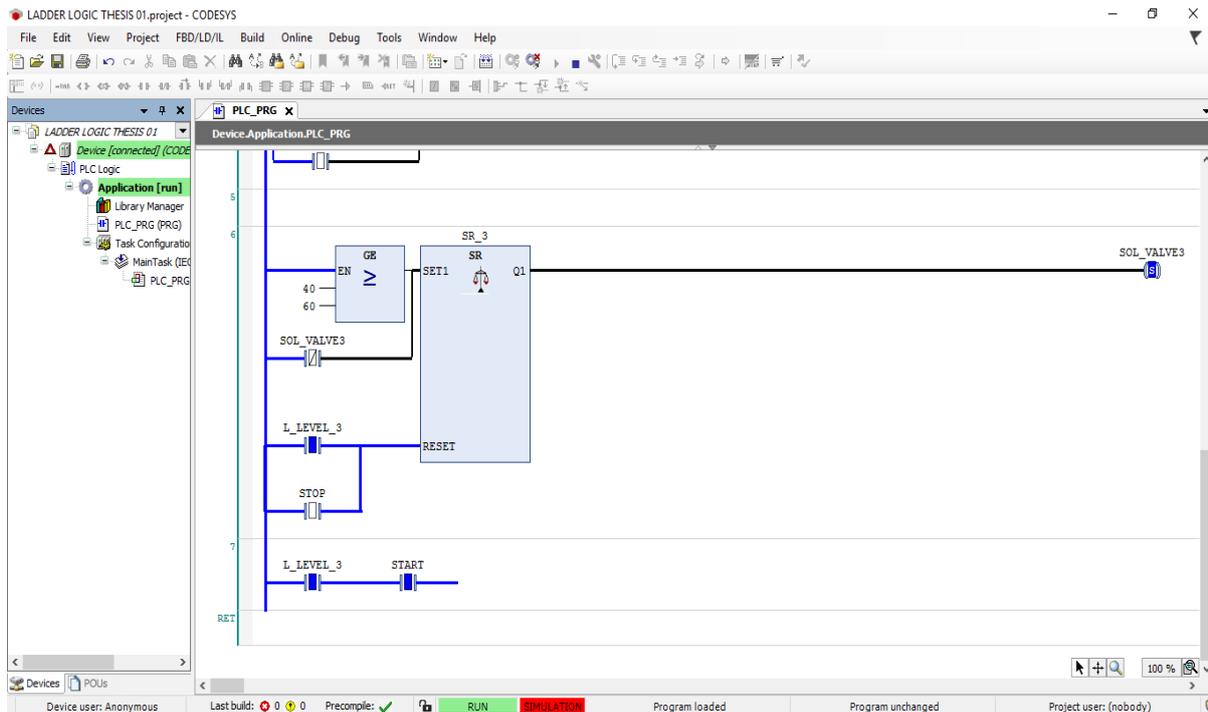
Figure 40: CODESYS Ladder programming screenshot.

Figure 40, shows the RESET condition on SR_3 flip flop. When L_LEVEL_3 is TRUE, the RESET condition is satisfied and this leads to the Shut-off of the Solenoid valve of tank 3 (SOL_VALVE3).

Now, the whole process is repeated from the START condition to the L_LEVEL3 and the operation goes on in loop until the Emergency STOP pushbutton is pressed. The STOP condition ceases the system operation immediately.

5.5. Step by step working process:

STEP	INPUT	OUTPUT
Step 1	L_LEVEL1&L_LEVEL2 -> TRUE	PUMP1 & PUMP2 -> ON
Step 2	H_LEVEL1&H_LEVEL2 -> TRUE	PUMP1 & PUMP 2 -> OFF
Step 3	H_LEVEL1&H_LEVEL2 -> TRUE	SOL_VALVE1 & SOL_VALVE2 -> OPEN
Step 4	L_LEVEL1&L_LEVEL2 -> TRUE	SOL_VALVE1& SOL_VALVE2 -> CLOSE
Step 5	H_LEVEL3 -> TRUE	AGITATOR -> ON HEATER -> ON
Step 6	TEMP_3 >= 40 DEG	AGITATOR -> OFF HEATER -> OFF
Step 7	TEMP_3 >= 40 DEG	SOL_VALVE3 -> OPEN
Step 8	L_LEVEL3 -> TRUE	SOL_VALVE3 -> CLOSE
Step 9	LOOP FROM START	LOOP FROM START

Table 3: Step by step working process using CODESYS.

The above table shows the step by step operations with respective input and relative output. Thus, the CODESYS development software, the proposed system was programmed and stimulated successfully. The working of the proposed system was as per the expectations and there were no shortcomings of the design experienced when simulating the system.

6. **System simulation using WPL Soft by DELTA:**

WPL SOFT by DELTA is freeware PLC programming software that is available in the official website of DELTA PLC manufacturer. WPL SOFT is program-editing software made for the DELTA DVP-PLC series programming without a license. Using the WPL soft, once can write PLC programming using Ladder Diagram (LD) logic. It also supports Sequential Function Chart (SFC) and Step Ladder Diagram (STL).

Unlike CODESYS, programming in WPL soft is more challenging and technical. The addressing of the components is a very important task in the WPL soft program development. In WPL sofe, there are fixed variable names for Inputs, Outputs, Memory or Auxiliary relay, Timers, Counters and Step. Each of the variable names have different register addresses.

Device	Item	Range
X	External Input Relay	X0 ~ X177, 128 points, octal
Y	External Output Relay	Y0 ~ Y177, 128 points, octal
M	Auxiliary Relay > General purpose	M0 ~ M511, M768 ~ M999, 744 points
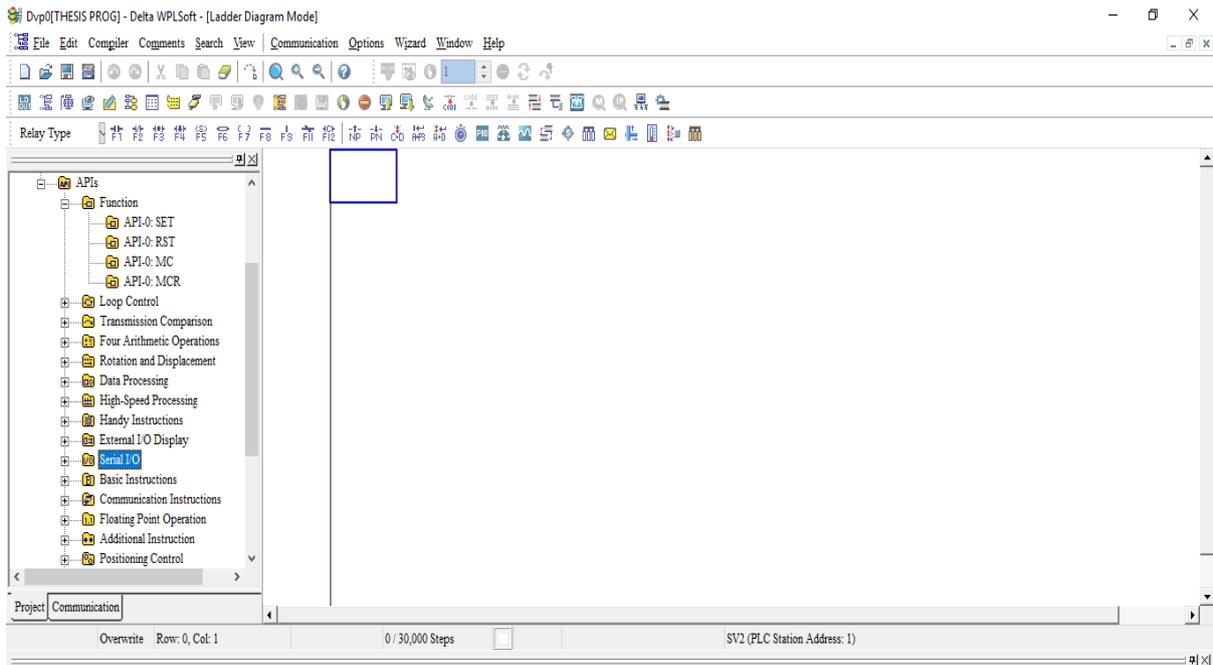
Figure 41: WPL soft programming software screenshot.

The picture above shows the User Interface of the WPL soft. The plain space on the right is used for inserting the Ladder diagram components from the Menu that can be seen above the programming space. On the left, there are list of functions and functional components available. They can be used in the ladder diagram to involve any specific functions. For example, SET and RESET function, Timers, Counters and Comparators etc.

In the Ladder Diagram of the above mentioned chemical mixing system, many number of Normally Open (NO) and Normally Closed (NC) switches are used. Thsose switches are switched open and close based on the inputs from the input sensors. The purpose of the PLC in the system is to Turn ON/OFF the two pumps that are connected to the thanks 1 & 2 based on the input from the Level Indicating sensors placed in the respective tanks. Then the PLC also actuates the output solenoid valves to discharge the liquids. The Ladder diagram is designed in accordance with the system function specification and it is simulated to check if the system is working as desired.

6.1. Complete Ladder Diagram using WPL Soft:

```
0    X0    X1    X2                                                    [SET    Y1]
     -| |--|/|--| |-

4    X0    X1    X3                                                    [SET    Y2]
     -| |--|/|--| |-

8    X0    X1    X4                                                    [RST    Y1]
     -| |--|/|--| |-

14   X0    X1    X5                                                    [RST    Y2]
     -| |--|/|--| |-

20   X0    X1    X4                                                    [SET    Y3]
     -| |--|/|--| |-

24   X0    X1    X5                                                    [SET    Y4]
     -| |--|/|--| |-

28   X0    X1    X2                                                    [RST    Y3]
     -| |--|/|--| |-

34   X0    X1    X3                                                    [RST    Y4]
     -| |--|/|--| |-

40   X0    X1    X6                                                    [SET    Y5]
     -| |--|/|--| |-

44   X0    X1    X6                                                    [SET    Y6]
     -| |--|/|--| |-

48   X0    X1                                          [CMP    D0    K5    M0]
     -| |--|/|-

57   M0                                                               [RST    Y5]
     -| |-

61   M0                                                               [RST    Y6]
     -| |-

65   M0                                              [TMR    T0    D7]
     -| |-

70   T0                                                               [SET    Y7]
     -| |-

72   X0    X1    X7                                                   [RST    Y7]
     -| |--|/|--| |-

78                                                                    [END]
```

52
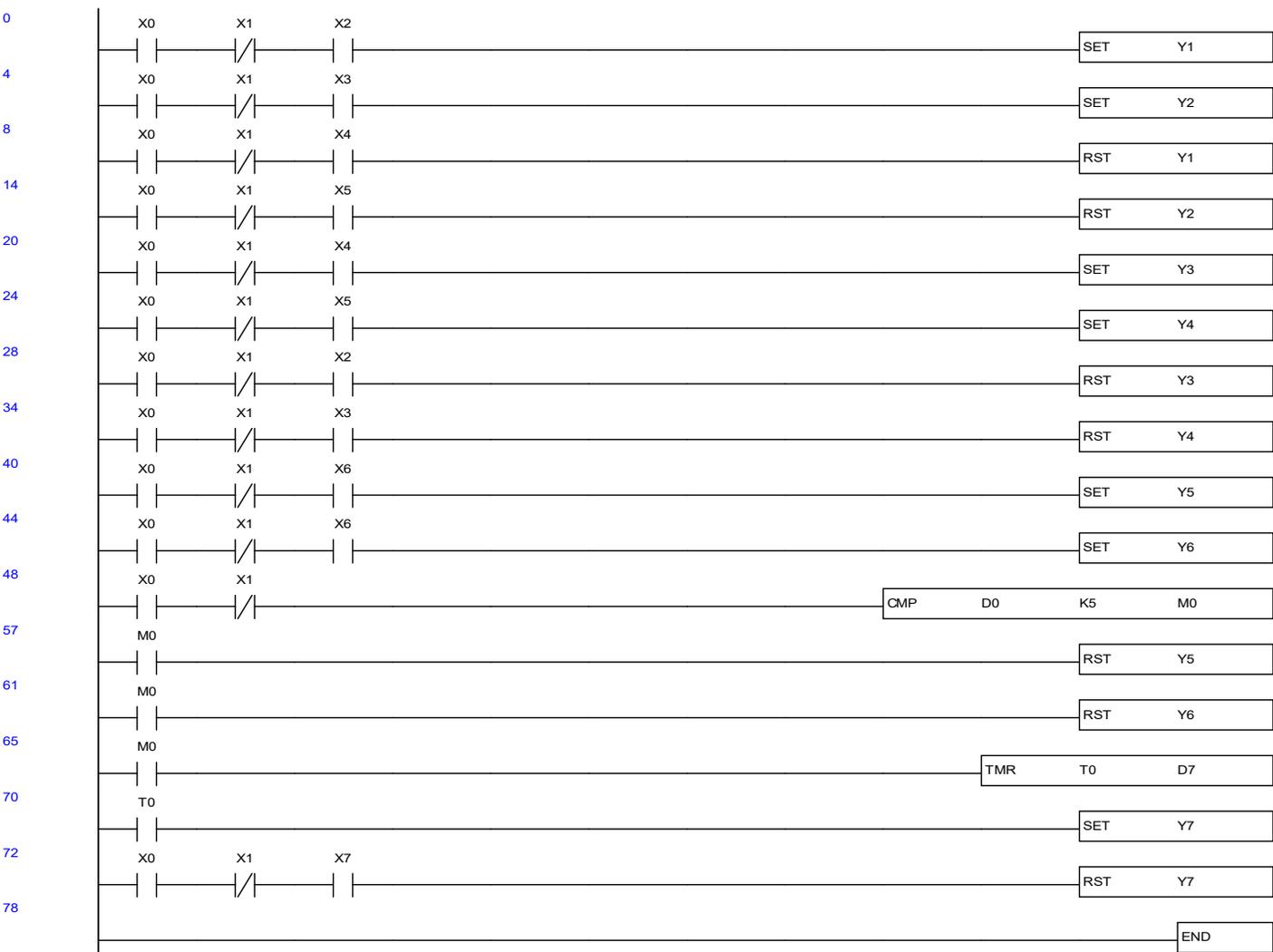
6.2. System Components and Explanations:

NO	COMPONENTS	FUNCTION	EXPLANATION
1	X0	Start	System ready and receiving inputs
2	X1	Stop	Emergency Stop
3	X2	Low Level tank 1	Low Level Liquid indication sensor in tank 1
4	X3	Low Level tank 2	Low Level Liquid indication sensor in tank 2
5	X4	High Level tank 1	High Level Liquid indication sensor in tank 1
6	X5	High Level tank 2	High Level Liquid indication sensor in tank 2
7	X6	High Level tank 3	High Level Liquid indication sensor in tank 3
8	X7	Low Level tank 3	Low Level Liquid indication sensor in tank 3
9	Y1	Pump 1	To fill liquid in tank 1
10	Y2	Pump 2	To fill liquid in tank 2
11	Y3	Solenoid valve tank 1	To Release or Discharge liquid from tank 1
12	Y4	Solenoid valve tank 2	To Release or Discharge liquid from tank 2
13	Y5	Agitator	To mix liquid in tank 3
14	Y6	Heater	To heat liquid in tank 3
15	Y7	Solenoid valve tank 3	To Release or Discharge liquid from tank 3
16	CMP (Comparator)	Temperature data comparison	Compares input temperature data from the sensor with the Pre-set reference temperature

Table 4: System components and explanations using WPL Soft.

6.3. System Components and their Data types:

NO	COMPONENTS	DATA TYPE
1	X0	BOOL (TRUE OR FALSE)
2	X1	BOOL (TRUE OR FALSE)
3	X2	BOOL (TRUE OR FALSE)
4	X3	BOOL (TRUE OR FALSE)
5	X4	BOOL (TRUE OR FALSE)
6	X5	BOOL (TRUE OR FALSE)
7	X6	BOOL (TRUE OR FALSE)
8	X7	BOOL (TRUE OR FALSE)
9	Y1	BOOL (TRUE OR FALSE)
10	Y2	BOOL (TRUE OR FALSE)
11	Y3	BOOL (TRUE OR FALSE)
12	Y4	BOOL (TRUE OR FALSE)
13	Y5	BOOL (TRUE OR FALSE)
14	Y6	BOOL (TRUE OR FALSE)
15	Y7	BOOL (TRUE OR FALSE)

16	CMP	Input – INTEGER (INT)
		NUMERICAL VALUE
		Output – BOOLEAN (BOOL)
		TRUE OR FALSE

Table 5: System components and their data types using WPL Soft.

6.4. Ladder Diagram working:

Initially, all the Inputs to the PLC are Null and the PLC is at the stand-by condition. The whole system is powered only when the **X0** (Start) pushbutton is pressed. When the pushbutton is pressed, the state of **X0** becomes TRUE and the system is set to ready condition and starts receiving input data from the input sensors.

The total input sensors in the system comprises of three sets of Level Indication sensor and a Temperature sensor, the Level indication sensors are used to detect the water level in the tanks. They can only detect if the water level in the tank is either HIGH or LOW, since those level sensors are Point detection sensors i.e. they are Boolean in nature. The temperature sensor measures the temperature of the liquid in the tank 3 and feeds the temperature data as an input to the PLC.

The initial starting condition of the process is to check that the Inputs **X2** (Low level of tank 1) and **X3** (Low Level of tank 2) are TRUE. If the condition is TRUE, the PLC turns ON the Outputs **Y1** (Pump 1) and **Y2** (Pump 2) respectively and the liquids are filled in tank 1 and tank 2.
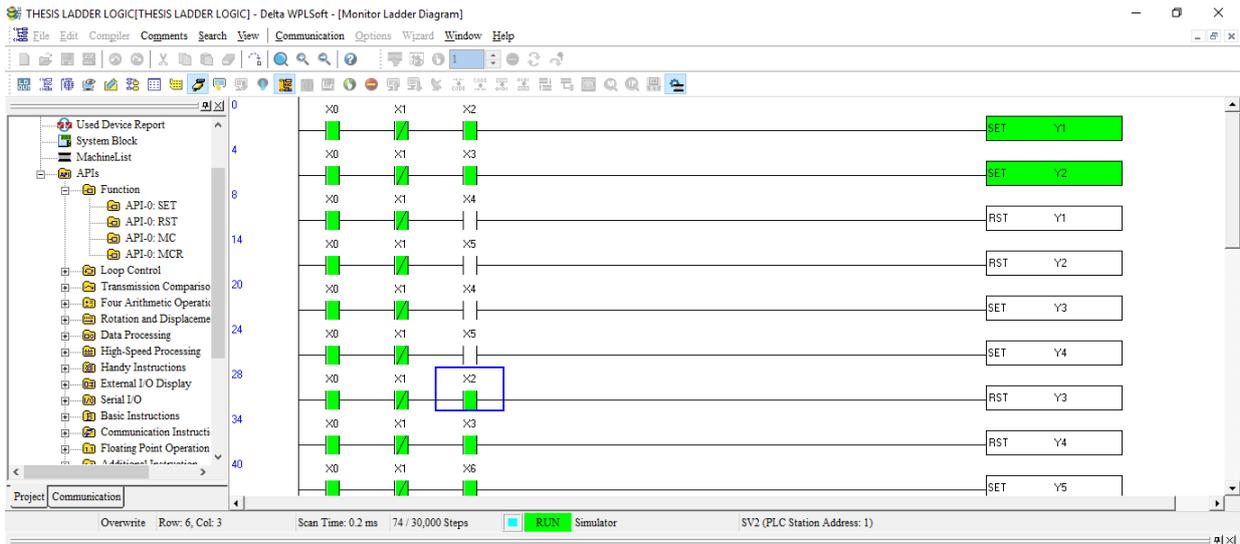
Figure 42: WPL soft Ladder programming screenshot.

From figure 41, it can be seen that, when the two Normally Open switches **X2** (Low Level of tank 1) and **X3** (Low Level of tank 2) are TRUE, the two respective outputs are triggered i.e. **Y1** (Pump 1) and **Y2** (Pump 2) are triggered to SET condition. The Pumps are turned-on and the liquids start to fill in tank 1 and tank 2 respectively.

When the water level is below the Low Level indication sensor, the Normally Open switch becomes Normally Closed switch i.e. from FALSE condition to TRUE condition. When the water level rises above the Low Level sensor, the switch becomes Normally open again. This brings the condition to FALSE.

When the two tanks are filled, the Low level indication sensor output becomes FALSE i.e. the **X2** and **X3** Normally Open again. The Pump 1 and Pump 2 are still in SET condition and are running. The Pumps are turned OFF only when the respective RESET condition is satisfied.

SET and RESET are basically LATCHES. SET will have different conditions to become true, when the TRUE condition is satisfied, it latches ON the output. Even when the condition is no longer TRUE, the latch is still on. Likewise, when the RESET condition is satisfied, the latch is unlatched. That is the basic working of the SET, RESET latches.
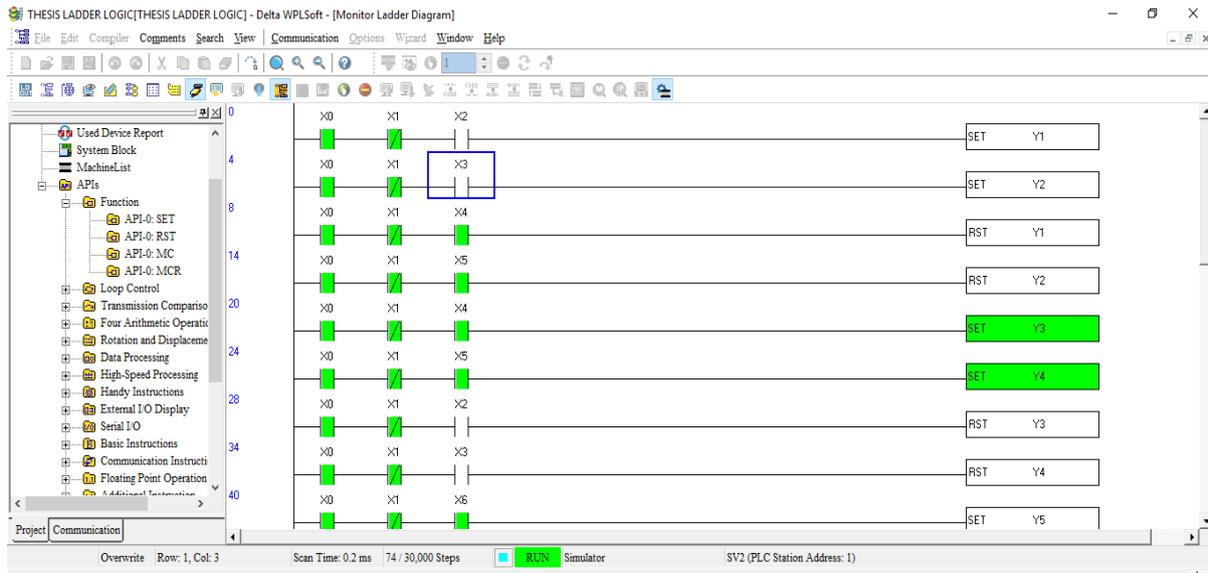
Figure 43: WPL soft programming screenshot.

From figure 43, it can be seen that, when tank1 and tank 2 are full, the LOW Level indication sensor is Turned OFF and the HIGH Level indication sensors **X4** (HIGH Level of tank 1) and **X5** (HIGH Level of tank 2) becomes TRUE and re Turned ON.

The RESET condition for turning off the two PUMPS is **X4** (HIGH Level of tank 1) and **X5** (HIGH Level of tank 2)to be TRUE. When **X4** and **X5** are TRUE, the PUMP 1 and PUMP 2 are Turned OFF. Thus, stopping the flow of liquid to tank 1 and tank 2.

The same condition of X4 and X5 to be TRUE, is used as the SET condition for Opening the Solenoid valves of tank 1 and tank 2 i.e. when the HIGH Level indication of tank1 and tank 2 are TRUE, two PUMPS are Turned OFF and at the same time, the SET condition is satisfied for Releasing or Opening of Solenoid valves.

When the solenoid valves **Y3** (SOLENOID Valve of tank 1) and **Y4** (SOLENOID Valve of tank 2) are in SET condition, the valve is in RELEASE or OPEN state. Now, the liquid from tank 1 and tank 2 are being discharged through the Solenoid Valves Y3 and Y4 to the main mixing tank, tank 3. The Solenoid valves will be open till the liquids are drained from the respective tanks.
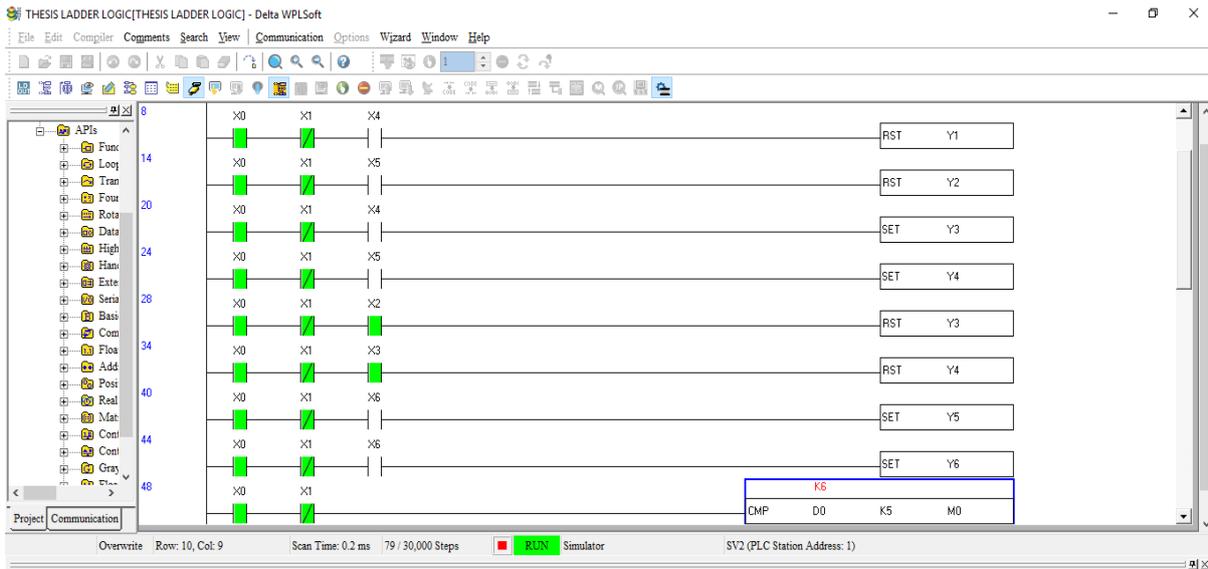
Figure 44: WPL soft programming screenshot.

Figure 43, shows the RESET condition of the two Solenoid Valves **Y3** (SOLENOID Valve of tank 1) and **Y4** (SOLENOID Valve of tank 2).

The two Solenoid Valves Y3 and Y4 are RESET when the liquid level of tank 1 and tank 2 reaches the LOW Level indication. The LOW Level indication sensors X2 and X3 become TRUE and this condition is used for closing the Solenoid valves Y3 and Y4. The solenoid valves Y3 and Y4 are shut-off and stop the discharge of the liquid from tank 1 and tank 2. From the figure 43, it can be seen that, the LOW Level indication sensor X2 and X3 output is used for Turning ON or SET the two PUMPS (Y1 and Y2) to Active state and RESET or Turning PFF the two Solenoid valves (Y3 and Y4).

The next step is the main process of the system i.e. mixing of liquids in tank 3. This step is reached when **X6** (HIGH Level indication sensor of tank 3) becomes TRUE. When the liquid from tank 1 and tank 2 are dumped in the main mixing tank, tank 3, at a certain point, the tank 3 is filled and the liquid reaches the HIGH Level indication.
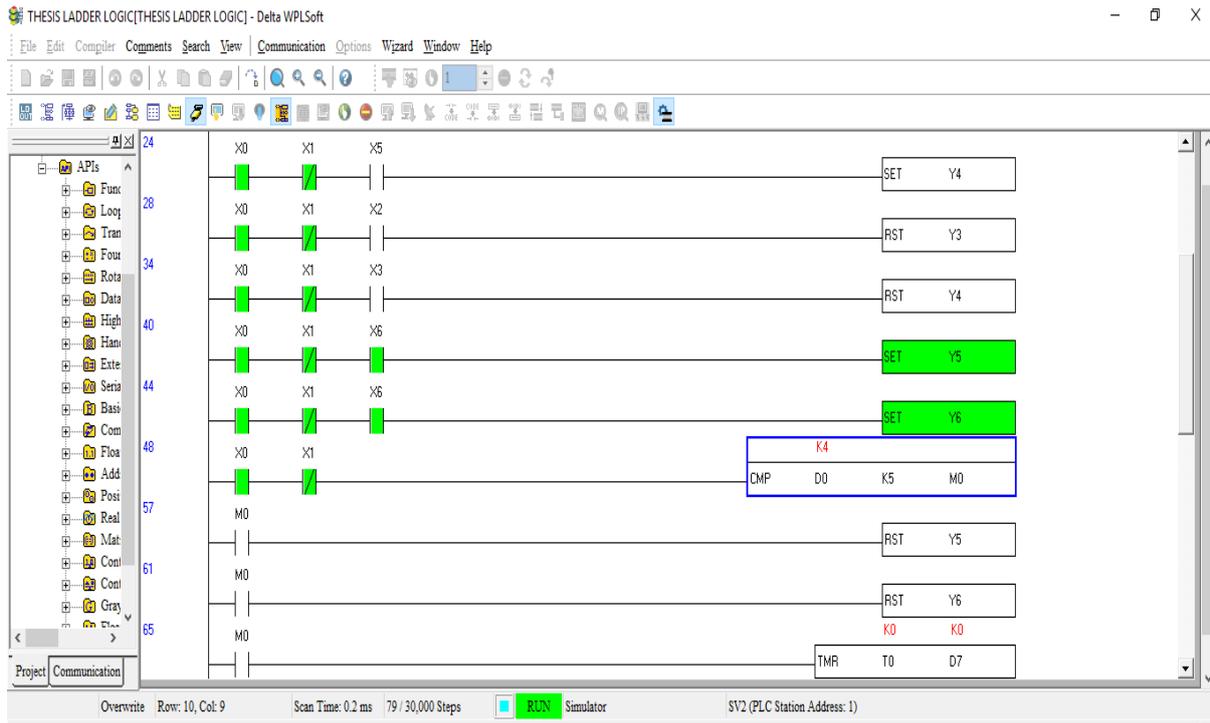
Figure 45: WPL soft programming screenshot.

From figure 45, it can be understood that the two system components are in SET condition. The system components are **Y5** (AGITATOR) and **Y6** (HEATER). They are the very important part of the liquid mixing system. The turning ON of Y5 and Y6 is achieved when the X6 is TRUE state.

The Agitator (Y5) mixes the liquid in the tank uniformly and the Heater (Y6) is used for heating the liquid and maintaining the temperature of the liquid at a desired temperature.

The temperature sensor connected to the tank 3 measures the temperature in real-time. In our system, the temperature reference point for the liquid in tank 3 is set at 40 deg C. The PLC is programmed in such a way that if the temperature of the liquid in tank 3 is greater than or equal to 40 deg C (TEMP>=40), the PLC will turn off the Agitator and the Heater.

In the above Ladder Diagram Programming, to implement the Temperature sensor, a Comparator (CMP) is used. The Comparator has two sources of inputs; source 1 is used to store the Reference Temperature that is used from comparing with the real time Temperature data from the Temperature Sensor. Source 2 is used for receiving Real-time Temperature sensor data. When the measured temperature is more than the Reference temperature (S2>S1), the comparator output will be TRUE. When the comparator output is TRUE, the

value is stored in the memory **M0**. For this purpose, a Normally Open switch with the same address M0 is inserted in the next rung. Therefore, when M0 is TRUE, the Normally Open switch becomes Normally Close switch.

When the output of the CMP (comparator) is TRUE, the PLC understands that the mixing operation has been completed and now the Agitator and Heater should be Turned OFF. The Agitator (Y5) and Heater (Y6) are SET or Turned On when the HIGH Level indication sensor of tank 3 (X6) is TRUE and they are RESET or Turned OFF when the Comparator (CMP) output is TRUE.
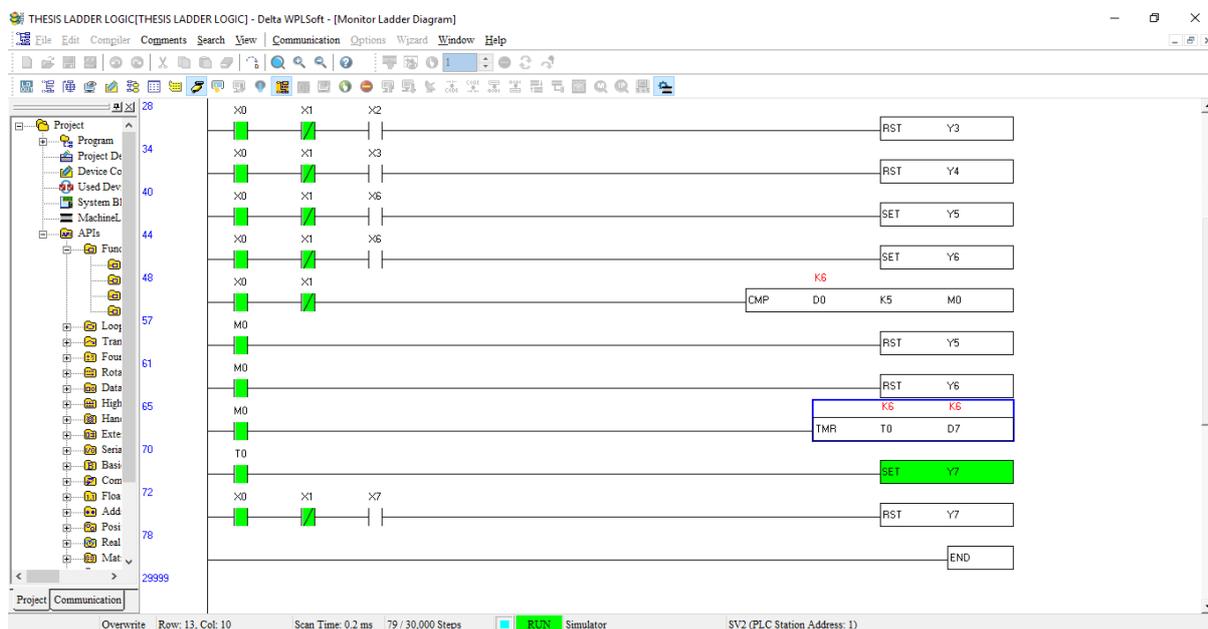
Figure 46: WPL soft programming screenshot.

Figure 46 shows that the **Y7** (Solenoid Valve of tank 3) is TRUE or in SET condition. This is achieved with the help of a Timer TMP latch. The Timer is used to provide a time delay between Turning OFF of Agitator and Heater and Turning ON of Solenoid valve of tank 3 (Y7). The time delay in introduced in order to facilitate the smooth operation between mixing of liquids and discharging them after the mixing is complete.

When Y7 is TRUE, the processed liquid in the tank 3 is discharged through the Solenoid Valve of tank 3. The discharged liquid is stored in the storage tank for further process. As the liquid is being discharged from, tank 3, the liquid level reduces and reaches the LOW Level indication sensor. When the water level is Low, X7 (Low Level sensor of tank 3) becomes TRUE. This condition is used as the RESET condition for the Y7.

When the water level is LOW, X7 (LOW Level sensor of tank 3) becomes TRUE, the Y7 (Solenoid Valve of tank 3) is RESET or Shut-off. Thus stopping the flow of liquid from tank 3. This operation marks the END of one Operating cycle of the chemical mixing process.
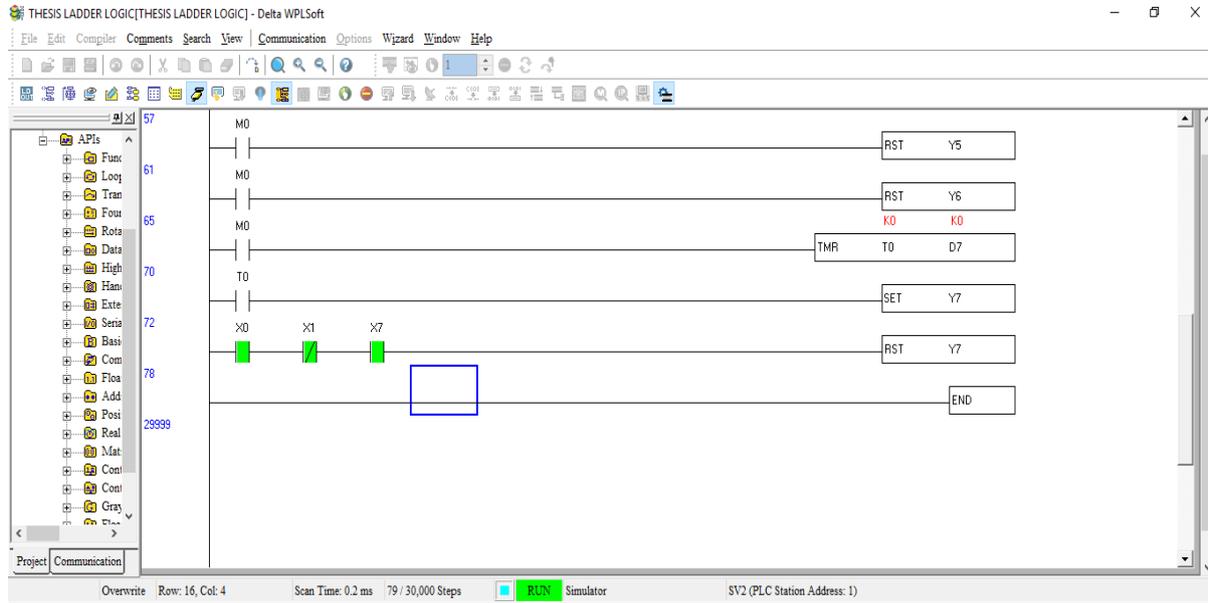
Figure 47: WPL soft programming screenshot.

Figure 47 shows the state of X7 (LOW LEVEL of tank 3) and Y7 (Solenoid Valve of tank 3). When X7 is TRUE, the Solenoid valve Y7 is RESET.

Now the whole process is repeated from the START X0 condition to the LOW Level of tank 3, X7 and the operation goes on in loop until the Emergency STOP X1 pushbutton is pressed. The STOP (X1) command ceases the system operation immediately.

6.5.   Step by Step working process:

STEP	INPUT	OUTPUT	OPERATION
Step 1	X0 -> TRUE		System in State of Readiness and receiving input.
Step 2	X2 -> TRUE	Y1 -> ON	LOW Level tank 1 -> PUMP1 ON
	X3 -> TRUE	Y2 -> ON	LOW Level tank 2 -> PUMP2 ON
Step 3	X4 -> TRUE	Y1 -> OFF	HIGH Level tank 1 -> PUMP1 OFF
	X5 -> TRUE	Y2 -> OFF	HIGH Level tank 2 -> PUMP2 OFF
Step 4	X4 -> TRUE	Y3 -> ON	HIGH Level tank 1 -> Solenoid Valve tank 1 ON
	X5 -> TRUE	Y4 -> ON	HIGH Level tank 2 -> Solenoid Valve tank 2 ON
Step 5	X2 -> TRUE	Y3 -> OFF	LOW Level tank 1 -> Solenoid Valve tank 1 OFF
	X3 -> TRUE	Y4 -> OFF	LOW Level tank 2 -> Solenoid Valve tank 2 OFF
Step 6	X6 -> TRUE	Y5 -> ON	HIGH Level of tank 3 -> Agitator ON
		Y6 -> ON	HIGH Level of tank 3 -> Heater ON
Step 7	CMP output -> TRUE	Y5 -> OFF	Temperature Sensor output TRUE -> Agitator OFF
		Y6 -> OFF	Temperature Sensor output TRUE -> Heater OFF
Step 8	CMP output -> TRUE	Y7 -> ON	Temperature Sensor output TRUE -> Solenoid valve of tank 3 ON
Step 9	X7 -> TRUE	Y7 -> OFF	LOW Level of tank 3 -> Solenoid Valve of tank 3 OFF

Table 6: Step by step working process using WPL soft.

The above table shows the step by step operations with respective input and relative output. Thus, using WPL soft programming, the proposed system was programmed and simulated successfully. The working of the proposed system was as per the expectations and there were no shortcoming of the design experienced when simulating the system.

7. Reliability Analysis of the Proposed System:

Reliability is generally defined as the Probability of Success [53]. Higher the reliability, lower the system failure. If a process control system should run continuously for a long time, the components of the system should be reliable. If a component has failed, it will affect the whole system process. Therefore, a system should have some backup to avoid such downtime. This is where the Reliability engineering is used.

Reliability engineering deals with the estimation, prevention and management of high level of engineering uncertainty and risks of failure of the systems [53]. Higher level of reliability can be achieved by good engineering, giving importance to design details, having proper standby support, etc. There are many techniques to access the reliability risks, they are Hazard analysis, Failure mode and Effect analysis, Fault tree analysis etc. from all the available techniques, Fault Tree analysis is the most widely used technique to access the failure of any system.
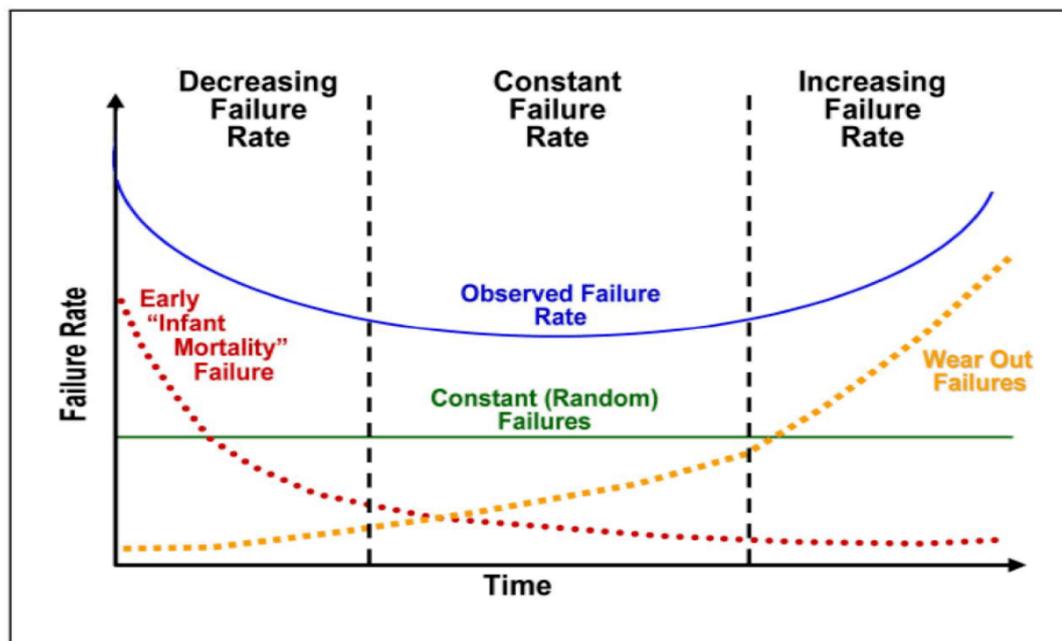
Figure 49: Reliability Curve [50].

The basic steps for reliability assessment are,

- Identifying the relevant Hazards. For e.g. root cause events, possible conditions, human errors, failure modes and mechanism.
- Assess the system risk by employing suitable analysis technique or testing.
- Propose a mitigation or solution. For e.g. change in requirements, design change, maintenance and suitable training with which the risks can be minimized or controlled.
- Finally, select the suitable solution and finalize the acceptable level of risk and cost/benefit analysis.

A system can fail in many ways, for e.g. failure can be caused by malfunction of the inputs or outputs, failure of the main processing system i.e. PLC in our case, software malfunction etc.

In our proposed system, the system failure can be caused by malfunction of the input sensors namely, Temperature sensor, Ultrasonic level sensors and malfunction of the PLC and in some case , failure of the software.

When the Ultrasonic level sensors being a primary input to the PLC, doesn't sense the liquid level, one input is lost and hence the system doesn't work. Since level sensors are the very starting point of the process, the whole system operation is obstructed. The cause of failure of the ultrasonic sensor may be due to aging, component failure, power supply failure, physical damage and environmental changes. Usually, ultrasonic sensors have longer life span since they don't have any moving parts and they are even less sensitive. To make the level sensors more reliable, choosing a better sensor with long life span, better fault tolerance, low power mode failure etc.

Temperature sensors too have failure chances like Ultrasonic level sensors. The cause of failure can be due to aging, Internal leaks, low insulation resistance, physical damage, environmental conditions, internal short-circuit etc. The reliability of the temperature sensor can be increased by choosing the sensor with better internal current handling, high insulation resistance, low hysteresis loss and not exceeding the temperature limit of the sensor and avoid direct contact with the liquid medium etc.

The failure of the PLC's can be due to numerous reasons with different effect on the PLC and its operations. The lifespan of the PLC is usually very high, for e.g. 100000 hours or 11 years in normal working conditions. The PLC can malfunction due to the failure of the hardware and the software . But they can also fail or malfunction due to interrupted power supply, electromagnetic interferences, overheating, I/O module failures, environmental failure, network and communication failures. Any one of the above failures can cause considerable amount of PLC downtime for maintenance, thus affecting the process or production. The reliability of the PLC can be increased by following a simple maintenance routine periodically and checking if all the I/O modules and networking modules are working fine. Providing the PLC with proper cooling setup can avoid the overheating and prevent the PLC failure. Industries should use electrical noise cancelling methods to filter noise interferences, thus preventing intermittent failure. Continuous power supply should be provided for better functioning of the PLC.
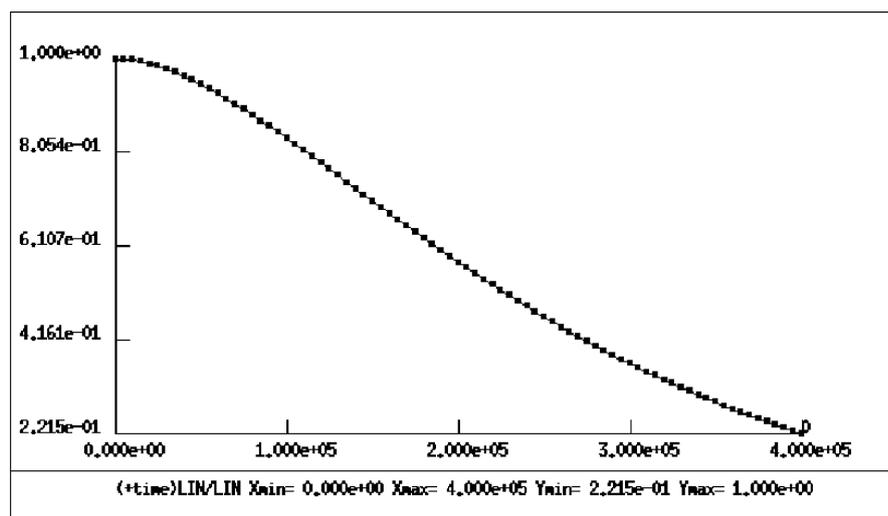
Figure 50: PLC reliability curve (time vs MTTF) [51].

The figure 50 shows the PLC reliability curve plotted with Time vs MTTF. MTTF is Mean Time To Failure. The reliability of the PLC reduces with time and the MTTF of the PLC increases with time (Aging). When the PLC is aging, the less reliable it becomes. The sudden failure of the PLC can be avoided by intermittent maintenance schedules, through which the state of PLC can be analysed and verified.

Software Reliability is an important attribute of software quality, together with functionality, usability, performance, serviceability, capability, installability, maintainability, and documentation. The production system can also fail due to the failure of the software that

runs the hardware components. When the software program running in a PLC gives wrong input command, the PLC follows the command and the output is undesired. Thus, the reliability of the software program or code used should be of high level. The software failure could be caused due to software bugs, misinterpretations in the software code, errors in the code, changes in memory directory, memory malfunction of the system running the software etc. To avoid the software failure, Adequate testing and debugging of the software program should be done.
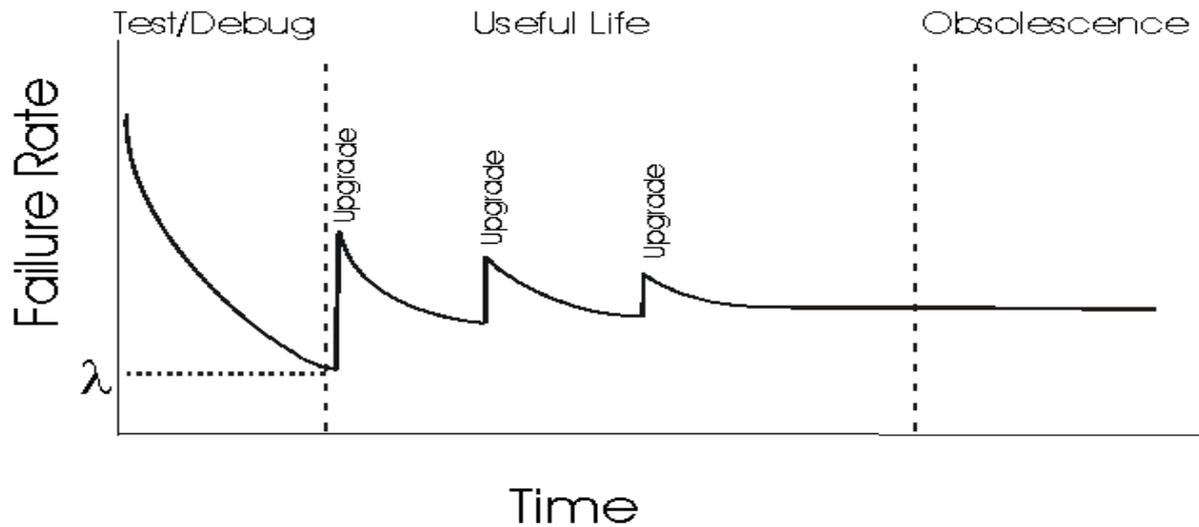
Figure 51: Software Reliability Curve [52].

In the figure 51, it shows the software reliability curve. It is plotted against Time vs Failure Rate. It is evident that the failure rate tends to maximise with increase in time. Therefore the software should have some testing and debugging occasional in order to avoid the unexpected failure.

8. Future Developments of the Project:

In this project, the PLC based Chemical Mixing system was designed and simulated successfully using the two widely used PLC programming softwares. The simulation of the design shows the desired output results. However, this project is limited to checking the working of the design only through software simulation. The future work should involve in developing the physical system with real-time inputs and accessing the respective outputs. Also, the proposed design is of a simple chemical mixer with limited inputs and outputs that was designed for the didactic purposes. they can be developed further to industrial standard

chemical mixers having advanced control technologies such as PID (Proportional Integral Derivative), PI (Proportional Integral) and PD (Proportional Derivative) controllers. Those controllers can be used to control the working of the chemical mixer in real-time by controlling various parameters like temperature, water level, mixing ratio, agitator speed etc. The automatic controller can do the control process on its own, without any invention from humans.

The selection of PLCs depends on the Complexity of the process to be controlled, number of Inputs and Outputs, Type of Programming that could be used, Cost Budget of the total project. Considering all the above prospects, the Arduino compatible 'CONTROLLINO' industry grade PLC could be used for the future development of the system. Controllino combines the open-source nature of the ARDUINO ecosystem with the safety and reliability of the industrial grade PLCs. The Controllino can be programmed using ARDUINO IDE which uses core C/C++ programming languages. There are also plenty of other programming softwares that could be used to program the Controllino.
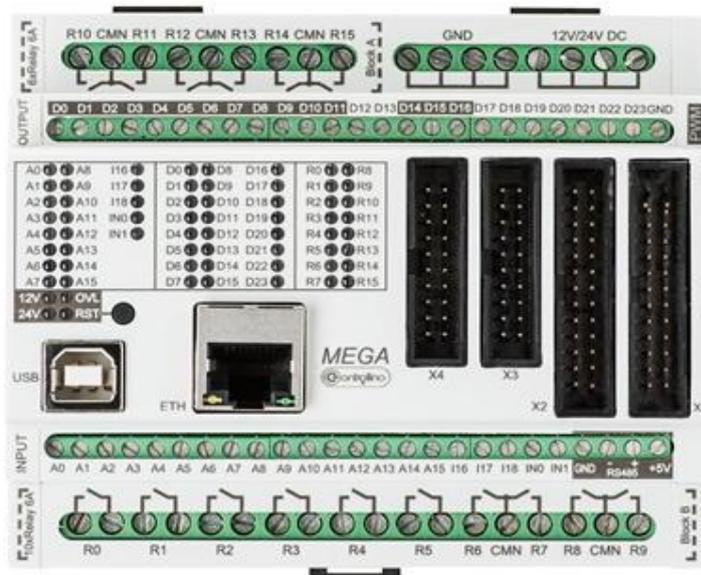
Figure 48: Controllino PLC [48].

The figure 48 shows the Controllino Mega, it has a total of 16 relay outputs and 24 digital outputs with a set of 21 analog inputs and outputs. The main microcontroller processor is ATmega 2560 from Atmel, which is 100 percent Arduino compatible.

9. Conclusion:

The main focus of this thesis was to provide hands-on experience for chemical engineering students that involve Programmable Logic Controllers (PLC) to implement Automatic Control Applications. This was achieved by designing a Chemical Mixing system that is controlled automatically by the PLC.

A detailed introduction to the Programmable Logic controllers with pictures were also discussed along with the different Input/output sensors and actuators. The wide array of PLC applications is also explained.

The working of the design was simulated using two different PLC programming software's and both simulation results were as desired. Ladder Diagram was used as the main programming language that was used to simulate the system design. The two different PLC programming software's are CODESYS and WPL SOFT by DELTA. The design simulation using the two software's were successful and the results were as predicted. The screenshots of the simulations are added to give better clarity to the working of the design.

The reliability analysis for the components and the system were also discussed. The Reliability of the Input/output sensors, reliability of the PLC and the software reliability were all discussed in detail with the cause of failures and the reliability measures to be taken.

From this work, chemical engineering students could understand the concept of Automation and Automatic control system that are implemented in the chemical industry. They could also understand the concept and importance of reliability of systems. This thesis could be used as a starting point for designing the complete didactic test bench for testing the reliability of components and systems.

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