Design and Analysis of Mechatronics System: A Case Study for Handling Hazardous Gases for Chemical Industry

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***Abstract*—This paper deals with the incidental release of toxic chlorine gas from the chlorine charging station to chlorine reactor in colour pigment manufacturing industry. The probable causes of the accidents are due to manual handling of toxic gases. The analysis and design of system is to be done to identify the possible errors and the unsafe activities and take safe preventive measures. These incidents have much learning which reveal many hidden facts about human safety in process industry and provide efficient tools for prevention of similar incidents in the future. It is a great opportunity to learn and design a safer plant in the future. The used toxic gases are controlled by Programmable Logic Controller (PLC) using Integrated Mechatronic approach for the automation of processes.**

***Keywords*— Process industry, PLC, Mechatronics, Case study**

I. INTRODUCTION

The Indian chemical industry has been one of the driving forces for industrial growth and has contributed immensely to the social and economic development of the country. The chemical manufacturing sector has grown phenomenally in the last three decades and today, manufactures wide range of organic chemical intermediates and finished products which find application in many areas.

A. Basic production process for pigment green manufacturing:

The phthalo green molecules are highly stable. They are resistant to alkali, acids, solvents, heat, and ultraviolet radiation. It is estimated that the worldwide production of phthalocyanine green is consumed by the paint and coating industry due to overall durability combined with outstanding economics of use. Phthalocyanine green is manufactured via 3 steps process.

Step1: The first step involves the manufacture of crude copper phthalocyanine blue. This crude is then halogenated to give the crude copper phthalocyanine green that is subsequently conditioned in the third stage to give the pigmentary product. Halogination takes place in a molten aluminium choloride eutectic mixture or in a solvent as a severe as sulphur dioxide, thionyl chloride or cholrosulphamic acid to give the crude green.

Step2: Halogenations' with chlorine gives bluer shade pigment green. Halogenations with bromine followed by the requisite amount of chlorine gives the yellower shade Pigment green 36. If the halogenations are carried out in a melt containing aluminium chloride, care must be exercised to avoid replacement of the copper with aluminium. Otherwise the durability of the resultant pigment will suffer markedly.

Step3: Finally the crude green is conditioned by either an attrition process or a solvent process to give the finished pigment.

B. **Applications of pigments**:

- Due to its stability, phthalo green is used in inks, coatings, and many plastics.
- In application it is transparent.
- The pigment is insoluble and has no tendency to migrate in the material.
- It is a standard pigment used in printing ink and packaging industry.
- It is also allowed in all cosmetics except those used around the eyes.

C. Causes of manual Handling of chemical process and its analysis:

- Chlorine is widely used for pigment making products throughout the world. It is also extensively used in the production of paper, dye stuffs, textiles, petroleum products, medicines, antiseptics, paints, insecticides, plastics and many other consumer products. The potential for leaks and spills of chlorine is present with its use. MHIDAS database indicated that 96 accidents of chlorine release to atmosphere occurred in the period 1964-1996 (Macro et al., 1998). These resulted in 39 deaths and over 2700 injured. They also showed that the contribution of human errors were 26% of incidents resulting in chlorine release. In general the chlorine leakage from a cylinder occurs due to the operational error, maintenance error; crack or rupture due to miscellaneous causes. In some cases human errors are also responsible for operational and maintenance errors. Figure 1. shows the generalized fishbone

- Diagram of accident causes that release of chlorine from chlorine charging cylinder.
- Human error defined by Chemical Manufacturer's Association (1990) as "any human action that exceeds some limit of acceptability (i.e. an out-of-tolerance action) where the limits of human performance are defined by the system". Figure 2. Shows categorization of human errors (HSE, 2005).

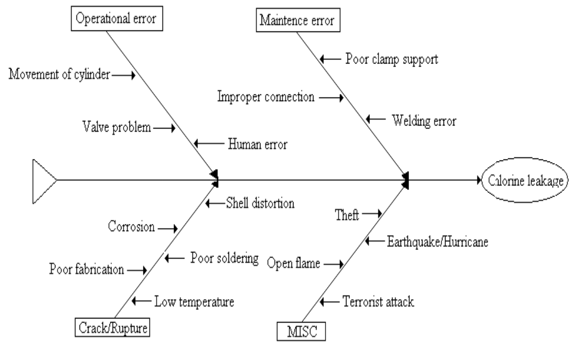

Fig. 1. shows the generalized fishbone Diagram of accident causes

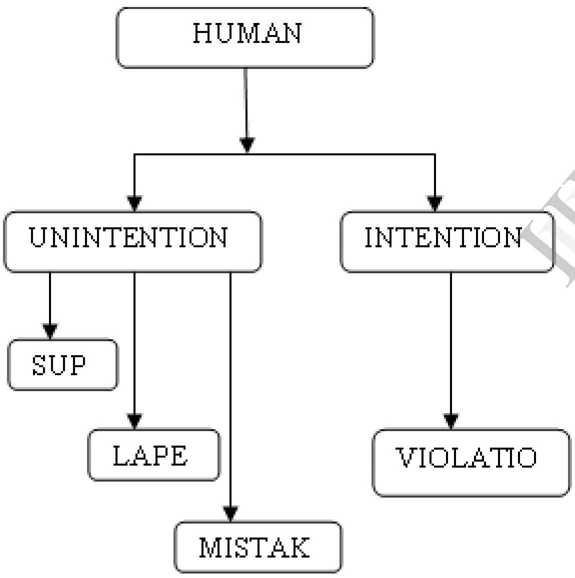

Fig. 2. shows categorization of human errors (HSE, 2005)

Sometimes human attention about various information, perceptions towards safety, capacity for remembering things and logical thinking not work properly as

1. Ignorance – one does not have the necessary/ knowledge for the activity;
2. Pseudo knowledge – one does not have the necessary knowledge for the activities, but believes they have the adequate knowledge;
3. Imprudence – one has the necessary knowledge for the activities but due to faulty thinking has convinced herself or himself that she or he is the exception to the rule.

The important task is to identify and reduce human errors for minimize the accident. Literature review shows that Human Reliability Analysis (HRA), Process Hazard Analysis (PHA) What-if analysis, HAZOP, Checklist, Failure mode and Effect analysis etc. use to predict the errors occurred which resulted an accident. Among them "what-if analysis" one of the useful applicable techniques to find out predictable human error, improve the safety levels and manages the risk successfully. This project deals with the description of the incident, identification of errors and the lesson learned from the accidental release of chlorine from chlorine pipe line.

D. Accident prevention and recommendation as preventive measures:

Figure shows the general accident prevention methodology in a fish bone diagram. There is a need for major precautions while working with chlorine, which when mis-handled is a very dangerous gas.

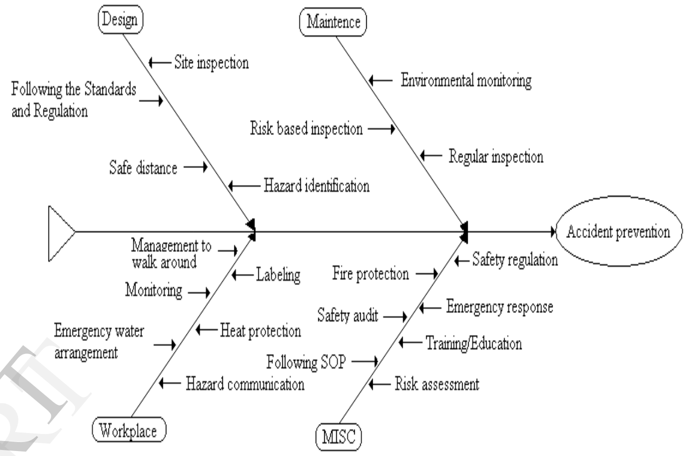

Fig. 3. General accident prevention methodology

Sectors of industry such as dyes and pigments, pesticides, drugs, leather chemicals etc.

E. Manual Handling of chemical processes:

Accidents in Chemical process industries constitute major threat to property and population because of the magnitude. With the rapid development in science and technology, several new innovations have come up and Chemical process industries deal with thousands of new chemicals and several processes. Nevertheless, there are innumerable causes that lead to disasters of major or minor in nature. So it would be of great use if we could collate and categorize all the disasters, which occurred in the past, so that the analysis results of these disasters are not only a useful lesson but also is helpful to prevent their recurrence.

Disaster is an accident / event that can lead to tremendous destruction to the environment, equipment, plant and people. The consequences of the chemical disaster in the chemical toxic gas release and dispersion. The various accidents due to these consequences are well known and gives prominent caution to prepare, practice and amend the / Toxic Disaster Management plans for each and every hazardous process industries and their material storage / Handling location.

Each chemical industry aims to achieve totally zero accidents potential. Therefore prevention, protection and suppression techniques have been applied to reduce the probability disaster.

The worst disasters of toxic releases have occurred in toxic chemicals like Chlorine cyclohexane etc. Disaster Management plan. The various stages of Disaster Management are Planning, Prevention, Preparedness, Response and Recovery.

We learn best through our own experiences in different phases of our life. Mistakes could be catastrophic in a chemical plant, but it is a great opportunity to learn and design a safer plant in the future. We must learn from previous incidents and develop design a safer plant in the future. We must learn from previous incidents and develop new procedures, practices and management systems.

These incidents have much learning which reveal many hidden facts about safety and provide efficient tools for prevention of similar incidents in the future. In spite of these lessons Indian industry continues to suffer.

Many tasks undertaken in the chemical industry involve the manual handling of chemicals, placing employees at risk of injuries and adverse health effects due to manual handling and/or exposure to chemicals. Manual handling chemicals in the industry can also expose employees to chemicals that may affect employees' health immediately or take months, or even years, to appear. These effects include: poisoning, irritation, chemical burns, sensitization, cancer, birth defects; and diseases of certain organs such as the skin, lungs, liver, kidneys and nervous system.

The severity of the health effects depends on the substance, nature and extent of the exposure. Chemicals that have the potential to harm health are known as hazardous substances. They may be solids, powders, liquids or gases, pure chemicals or mixtures. When used in the workplace, these chemicals often generate vapors', fumes, dusts and mists. A wide range of chemicals are classified as hazardous. These may enter the body in a number of ways, depending on the chemical and how it is used (the nature of the work).

The major routes of exposure to hazardous chemicals in the workplace are:

• Breathing in (inhaling) vapours, fumes, dusts and mists;
• Absorption into the body from direct contact with the skin, eyes, etc.; or
• Swallowing (ingesting) or injecting into the body (for example, unclean hands, smoking or contaminated food).

→ Manual handling of chemicals can create extra risks compared to other manual handling jobs and tasks:

Employees manually handling containers of chemicals may adopt awkward postures and movements in order to avoid contact with residues and contaminants on the outside of containers or being exposed to vapours or fumes from open containers; or avoid spillages while carrying, emptying, decanting, measuring and mixing chemicals. The use of protective clothing and equipment can increase manual handling risk by restricting movement, limiting grip, increasing the physical effort required to do the job and increasing heat stress. Sometimes when completing manual handling tasks, protective clothing and equipment may be used incorrectly, increasing exposure to chemicals. Measures to reduce or eliminate the need to use protective clothing and equipment can reduce manual handling risks. Reducing manual handling risks associated with protective clothing and equipment can also mean such equipment is used properly because it is more comfortable (e.g. less sweating) and interferes less with doing the job at hand.

→ Implementing manual handling risk controls can reduce exposure to chemicals

Manual handling risk controls can reduce exposure to chemicals by preventing damage to chemical packages and reducing spills, leaks and clean ups when:

• Delivering, unloading and storing chemicals; and
• moving chemicals within the workplace and storing them in work areas.

Changing the packaging – e.g. size, shape and weight – can reduce manual handling risks and exposure to chemicals.

II. BASICS OF CHLORINE GAS AND CHLORINATION PROCESS

Chlorine is a toxic, corrosive gas that can cause severe burns if inhaled or upon skin contact. It is a greenish-yellow non flammable liquefied compressed gas packed in cylinders under its own vapor pressure. It form fume on contact with moisture in air. The degree of fuming is related to the amount of humidity in the air. It is also an oxidizer and will support the combustion. Products of combustion gases are generally toxic in nature. Chlorine exposure occurs through inhalation or skin or eye contact. Inhalation irritates the mucous membranes of the eyes, nose, throat, and lungs. Prolonged exposure or exposure to high concentrations is fatal.

1-3 ppm mild mucus membrane irritation.
5-15 ppm moderate irritation of upper respiratory tract .
30 ppm immediate chest pain, vomiting, dyspnea, and cough.
40-60 ppm toxic pneumonitis and pulmonary edema.
430 ppm lethal over 30 mins.
1,000 ppm death within a few minutes.

Although inhalation is the primary mode of exposure, direct skin contact with gaseous or liquid chlorine may result in chemical burns as the chlorine reacts with moisture on the skin. In addition, the extremely cold temperatures associated with liquid chlorine and vaporized gas escaping from pressurized containment can cause frostbite. The exposure limits are as follows:

OSHA: PEL=1 ppm
ACGIH: TWA/TLV = 0.5 ppm
NIOSH: IDLH=10ppm

A. Chlorination process for pigment chemical industry:

Chlorination is generally highly exothermic. Both saturated and unsaturated compounds react directly with chlorine, the former usually requiring UV light to initiate homolysis of chlorine. Chlorination is conducted on a large scale industrially, major process include routes to 1,2-dichloroethane and various chlorinated ethanes as solvents. Competitive with direct chlorination (use of Cl_2) is oxychlorination which uses hydrogen chloride in combination with oxygen.

Clorination is required in green pigment. Phthalocyanine green is a phthalocyanine blue pigment where most of the hydrogen atoms are replaced with chlorine. The strongly electronegative chlorine atoms influence the distribution of the electrons in the phthalocyanine structure, shifting its absorption spectrum. It is made by chlorination of the phthalocyanine blue as a melt of sodium chloride and

aluminum chloride, to which chlorine is introduced at elevated temperature.
The phthalo green molecules are highly stable. They are resistant to alkali, acids, solvents, heat, and ultraviolet radiation.

B. Working principle:

Chlorine gas under pressure (pressure of chlorine cylinder) goes into the regulator. In the inlet valve the pressure is reduced to 1,2 bar. Through the inlet valve the chlorine gas goes through the control valve, where the desired amount is set as per the process requirement i.e. about 0.4 to 0.5 kg/cms, into the measuring tube. The desired amount of chlorine gas then goes through the chlorine pipe into the reactor vessel, where it is mixed with a mixture of aluminum chloride and a phthalocyanine blue pigment. The pipeline is equipped with non-return valve, to prevent the fumes enter into the system. rotameter is equipped to measure flow rate.

III. BASICS OF MECHATRONICS

Mechatronics is "the synergistic integration of Mechanical Engineering with Electronics and intelligent control algorithms in the design and manufacture of products process". Synergistic integration means the mechatronic engineers have to study the aspects of engineering that are vital for the design and manufacture of products, process. A graphical representation of Mechatronics is shown in Figure 4.

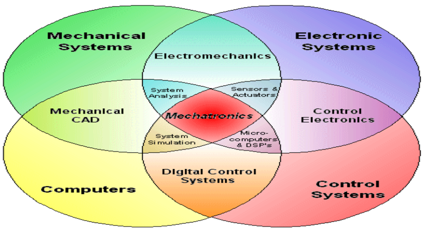

Fig. 4. Graphical representation of Mechatronics

The main technical areas under the research and development domain mechatronics are:
• Motion control,• Robotics,• Automotive systems,,• Intelligent control, Actuators and sensors,• Modeling and design,• System integration,• Manufacturing,• Micro devices and optoelectronics,• Vibrations and noise control

A. Evolution of Mechatronics:

Mechatronics has evolved through the following stages:
• **Primary Level Mechatronics**: Integrates electrical signaling with mechanical action at the basic control level for e.g. fluid valves and relay switches
• **Secondary Level Mechatronics**: Integrates microelectronics into electrically controlled devices for e.g. cassette tape player.
• **Tertiary Level Mechatronics**: Incorporates advanced control strategy using microelectronics, microprocessors and other application specific integrated circuits for e.g. microprocessor based electrical motor used for actuation purpose.

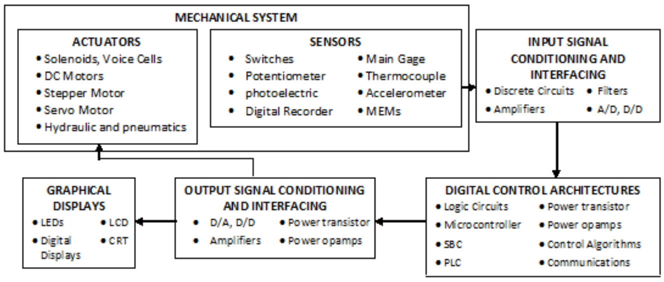

Fig. 5. Mechatronics system

The actuators produce motion or cause some action.
• The sensors detect the state of system parameters, inputs, and outputs devices
• Digital devices control the system.
• Conditioning and interfacing circuits provide connections between the control circuits and the input/output devices.
• Graphical displays provide visual feedback to users.

B. Mechatronics as Design Philosophy:

It is "a design philosophy" where mechanical, electrical, electronic components and it should be considered together in the design stage to obtain an compact, efficient, and economic product design rather than designing the components in stages separately. This is illustrated in figure
Design trends in Mechatronics are oriented to reduction of hardware parts of the systems and increasing the software option volume to improve of the system functionality and system reliability. Typical aspects of the Mechatronics area are the applications of new physical principles, (smart) materials, electronic and microelectronic systems, complex computing and controlling technologies and progressive production processes.

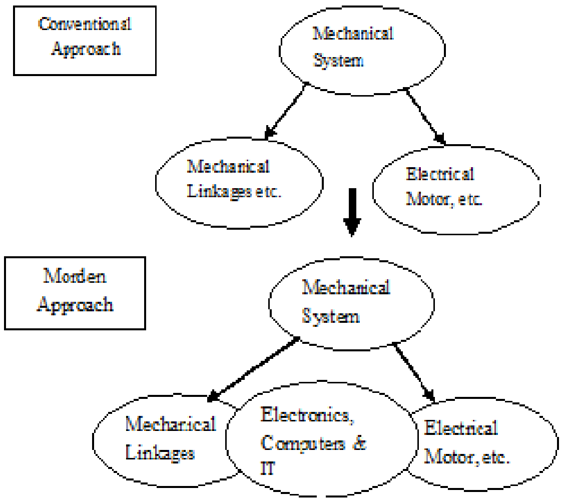

Fig. 6. Design trends in Mechatronics

Mechatronic systems are to be built, designed, monitored, controlled and simulated using hardware and software tools (modularity), work bench (platforms) and techniques, considering hardware software integration parameters such as modularity, scalability, extendibility, flexibility, interoperability, interchange ability etc.

C. *Measurement Systems:*

A fundamental part of many mechatronic systems is a measurement system composed of the three basic parts:

- **The transducer** is a sensing device that converts a physical input into an output, usually a voltage.
- **The signal processor** performs filtering, amplification, or other signal conditioning on the transducer output.
- **The recorder** is an instrument, a computer, a hard-copy device, or simply a display that maintains the sensor data for online monitoring or subsequent processing.

D. *Modeling and Simulation:*

The behavior of engineering system is studied through modeling and simulation. State of the art simulation, measurement and test technique enable us to accurately predict performance. In a conventional design approach, components of a physical system are designed in isolation and test its feasibility physical prototypes are made. Based on the prototype test results modifications are carried out. This modeling and simulation together is also referred as virtual prototyping, as it serves the purpose of physical prototypes without really making one. The challenges in modeling and simulation or in virtual prototyping are:

1. The methods and ways to write the system equations of motions so that computers take less time to solve; and
2. The numerical methods used to solve the equations so as to obtain realistic results without large numerical errors, which have nothing to do with the physical systems.

E. *Application of modeling and simulation:*

- Concept design: a new idea to be examines / discussed / communicated.
- Design refinement: re-run program with change input data.
- Design verification: study performance.
- Test planning: predict behavior before a real test.
- System re-construction: study a failure.
- Teaching and training: useful tool for teaching and training.

IV. INTEGRATED APPROACH OF MECHATRONICS TO PROCESS

Charging of chlorine gas for reactor to manufacture pigment.

A. *Existing system:*

Presently the charging of chlorine gas has been done manually by conventional method. Chlorine tonner is attached to the pipeline manually. The liquid chlorine is passed to chlorine vaporizer where the liquid chlorine is converted into gasses form. The liquid chlorine gases controlled by regular flow control valve. The chlorine flow rate is measured by rotameter and the consumption is recorded.

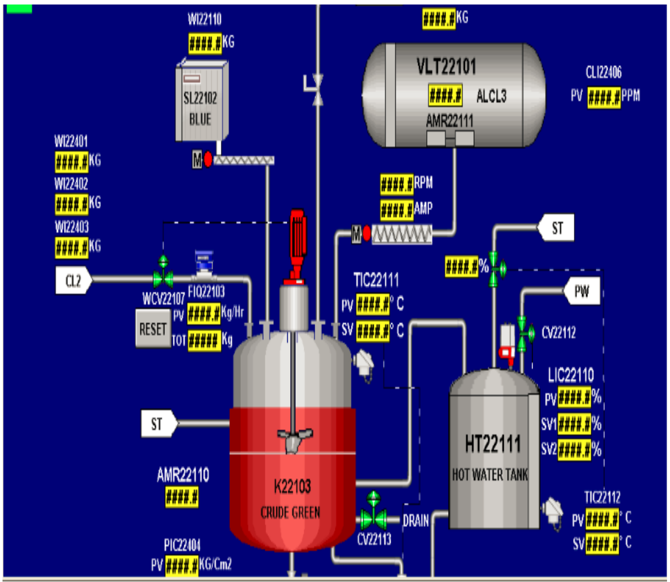

Fig. 7. Existing system of charging of chlorine gas

B. *Proposed Automated System -- Eliminates Human Error and Ensures Human Safety:*

Implementation of automated systems for charging chlorine gas in chemical process to ensure safety in hazardous environments. Human Safety being a primary concern, especially in hazardous chemical plants, requires close monitoring of all processes. Automated process control systems eliminate human errors and give early warning of failures.

Around 40 ton of chlorine gas/month processed in plant. The gas is piped to the reactor vessel and the liquids vaporised in the vaporiser. This process of manual charging is "critical" because of the high volumes of liquid/vapour chlorine gas that are released from them system. Safety, reliability and environmental concerns required the implementation of a state-of-the-art control system.

→ Integration between Standardised plant and field control systems:

Programmable Logic Controllers (PLC) in chlorination gas charging process can be used to handle number of active input-output points. A separate and independent PLC system is required for emergency shutdown system (ESD) to fulfil safety and reliability criteria. Logic controls handled by the PLC system, based on the operation function and didn't require any manual intervention.

The SCADA/DCS could handle the analog controls. These two systems could then be connected by a gateway PLC that allows data to be passed between the systems. A careful coordination of various dangerous processes is required for a complex work. The control system for chlorine gas utilisation can be a hybrid SCADA/PLC design.

PLC provided discrete control for: Equipment start/stop/open/close, operating and restart sequence, critical announcements, emergency and unit shutdowns (ESDs & USDs), depressurisations, chlorine detector sensor, flow meter, control valve, waterpump and blower. PLC also monitored and controlled the equipment, local displays and workstations by interfacing with rotating equipment panels and monitors. Both SCADA and PLCs collected data.

The information gathered by the PLC was sent to the SCADA and then the set point changes were communicated to the PLCs.
A single PLC performed the PID control, ESD control, process alarm and station service monitoring at each location, communication with redundant PLC-to-SCADA gateways within plant. The gateways can be linked to the SCADA control room through fibre-optic links. Area PLCs had to be fail-safe, if the failure of the main and backup PLCs in any one area were to result in the shutdown of that area of the plant only. Equipment monitoring systems would be cost effective if e traditional lamp boxes and chart recorders are replaced with reliable automated monitoring systems. Savings it made in wiring alone paid for the control system. The issue of safety of employees also was resolved &human errors eliminated. Operations could be easily monitored and warnings regarding any failure could be conveyed to the plant personnel immediately through the use of networked computers and display boards.

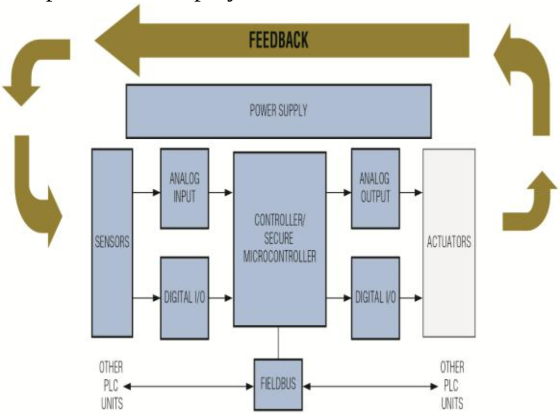

Fig. 8. Proposed control system

Input:	Output:
• RTD	Digital O/P
• Thermocouple	Analog O/P
• Level transmitter	Analog O/P
• Pressure transmitter	Analog O/P
• ON/OFF valve	Analog O/P
• PID Valve	Analog O/P

C. Objectives of proposed system:

Our objective is to minimize human error and maximize performance of system by automation, the decision to automate or of how much to automate should be dealt with like any design decision. There are a number of variables to consider when designing a system that requires a combination of human input and automated control. In addition to discussing these variables, it is important to determine a number of foundation definitions and considerations of human engineering to ensure each situation can be based on consistent principles. Human error consists of any significant deviation from a previously established, required or expected standard o f human performance". From the point of view of designing, operating and maintaining an industrial system, this one provides a working foundation.
When humans make errors and cause a system to fail, it doesn't fail due to any one particular reason. It fails because of the kinds of people operating the system, the amount of training they have received and the level to which they are physically or mentally able to cope with the way the system was designed. The system failure can be a function of the operating procedures provided for the person and the environment in which the people are work.
The aim of automation of a system is to relieve humans of time-consuming, human's safety and laborious tasks, to speed the operation, to increase production rates, to extend an operations to a longer shift or even to continuous production, to reduce system inefficiencies or to ensure physical specifications are maintained and consistent. Automated operations are thought to be more efficient, reliable and accurate than humans.

V. CONCLUSION

The PLC based control system improves the existing control functions. It reduces maintenance, improves reliability and it is easier to operate and maintain. It supports various types of operator interfaces, provides additional alarming and diagnostics capabilities and is capable of interfacing to other computers, PLC's or DCS systems that cover everything from process plant to electronics to basic data acquisition. They leverage various sensor types and feedback mechanisms to monitor and control the local environment and system/machine interactions by collecting, storing and analyzing data. Acquiring data from sensors involves precision measurement and the processing of very low values or small changes in Analog voltages/currents.

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