Major Project Report On

Design And Development Of Instrumentation And Control System Hardware And Software Modules For The Cryogenic Test Facility

Submitted in partial fulfillment of the requirements

for the degree of

MASTER OF TECHNOLOGY

in

INSTRUMENTATION AND CONTROL ENGINEERING

(Control and Automation)

At

INSTITUTE FOR PLASMA RESEARCH

By

Yama Joshi

14MICC13

INSTRUMENTATION AND CONTROL ENGINEERING SECTION

DEPARTMENT OF ELECTRICAL ENGINEERING

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

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Under The Guidance Of

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Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Instrumentation and Control Engineering at Nirma University and has not been submitted elsewhere for Degree.
2. Due acknowledgement has been made in the text to all other materials used.

- Yama Joshi
14MICC13

Undertaking for the Originality of the work

I, Yama Joshi, Roll.No.14MICC13, give undertaking that the Major Project entitled "Design And Development Of Instrumentation And Control System Hardware And Software Modules For The Cryogenic Test Facility" submitted by me, towards the partial fulfilment of the requirements for the degree of Master of Technology in Instrumentation and Control Engineering (Control and Automation) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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- Yama Joshi

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Abstract

The Helium plant test facility needs compressors and turbines as compression and expansion machines respectively to produce cold helium for test of cryogenic components. Cryogenic turbines are significantly smaller in size compared to those for room temperature applications, but rotation speed is high, about few lakhs of rpm and hence it has contactless gas bearings. This test facility will be used to test these turbines, compressors ,different types of plate-fin heat exchangers and helium purifiers. Hence, such cryogenic test facility needs large number of sensors (temperature, pressure, flow, speed, vibration, level etc) and valves for diagnostic purposes. The project work includes the design of the control system hardware and the software architecture and process logics developed for different operational scenarios of cryogenic test facility. To operate the facility, PLC based hardware having three nodes with the performance in the order of 100 msec over Ethernet for data exchange between nodes is required. Around 500 I/O channels including pressure control valves, on/off valves, temperature sensors, absolute and differential pressure measurement points, flow measurements, one set of speed measurement sensors, one set of vibration sensors, level sensors, etc are required to communicate with PLC. Process flow chart (PFC) logic and control algorithms development along with a prototype simulator to evaluate the concepts. Operational sequence of different components with rate of opening/closing (including PID loops) of valves has been conceptualized for safe operation during normal and off-normal operations in the test facility. Concepts to be developed for data management like logging, storage, display, process, access, generation of experiment recipes for automation in operation using Siemens PLC.

List of Abbreviation

CORS = Compressor and Oil Removal System

ORS = Oil Removing System

MCD = Main Control Dewar

SCMS = Superconducting Magnet System

SST = Steady State Superconducting Tokamak

HRL = Helium Refrigerator Liquefier

GHe = Gaseous Helium

LHe = Liquid Helium

SCADA = Supervisory Control and Data Acquisition System

PV = Process Variable

SP = Set Point

CO = Controller Output

MV = Manipulated variable

PLC = Programmable logic controller

FB = Function block

FC = Function

SCL = Structured Control Language

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Chapter 1

Introduction

1.1 Institute Overview

Institute for Plasma Research is an autonomous R & D organization under authority of department of atomic energy, Government of India located near west banks of river sabarmati in Gujarat, India. The institute is largely involved in theoretical and experimental studies in plasma science including basic plasma physics, magnetically confined hot plasmas and plasma technologies for industrial application. FCIPT, ITER-India and CPP-IPR, located in Gandhinagar and Guwahati are three divisions under IPR. It has a scientific and engineering manpower of 200 with core competency in theoretical plasma physics, computer modeling, ultra high vacuum, superconducting magnets and cryogenics, microwave and RF, pulsed power, computer-based control and data acquisition and industrial, environmental and strategic plasma applications. The institute has helium refrigerator/liquefier plant of approx. 1KW capacity for tokamak and plasma applications, which is operating successfully[1].

1.2 Helium Refrigerator/Liquefier (HRL) Plant

Plasma is fourth fundamental state of matter. When gas or air is ionized, its atoms or molecules will turn into positive and negative ions which form the plasma. It has similar conductive properties that of metals. Plasma can also be created by application of an electric field on a gas. Like gas, plasma does not have a definite shape or a definite volume unless enclosed in a container. Confining plasma requires strong magnetic field and to generate the strong magnetic field superconducting magnets are used. Superconducting magnets should be cool down to very low temperature to lose their resistance and make it super conductive. To cool down the magnets at very low temperature, liquid helium is used. In the atmosphere helium is available in gaseous form so helium liquefier is used to liquify helium.

The process of cooling a gas to a temperature below its critical temperature so that liquid can be formed at some suitable pressure which is below the critical pressure is called Liquefaction. It is the physical conversion of gas into liquid state. The gas is first compressed to an elevated pressure using a compressor at atmospheric temperature and just above atmospheric pressure. This highly compressed gas is then passed through a series of counter-current heat-exchangers and an expansion engine to remove some of its energy. Turboexpanders are used to expand helium gas which is of very small size because of requirement of small passages in expander, but operated at very high speed of about few lakh of rpm. Expansion through turboexpander and expansion engine is isentopic. Expansion through throttling valve (Joule-Thompson valve) is isenthalpic and used where a phase change is required. Operating J-T valve needs precooling of gas to its inversion temperature otherwise it will give heating instead of cooling. After expanding to a certain lower pressure below the critical pressure, cooling takes place and some fraction of gas is liquefied. The cool, low-pressure gas returns to the compressor inlet through a recycle stream to repeat the cycle. The counter-current heat exchanger warms the low- pressure gas prior to recompression, and simultaneously cools the high-pressure gas to the lowest temperature possible prior to expansion.

Liquid helium at 4.5K is required for the Controlled cool down of the SCMS (Superconducting magnet system) of the Tokamak. The HRL has refrigeration capacity of about 650 W at 4.5 K and simultaneous liquefaction capacity of 200 l/hr. using approximately 1 MW of power. Main components of HRL are (i) Compressor station (ii) Oil removal system (iii) Purifier system and (iv) Cold box with Main control Dewar (MCD). Each subsystem is considered as standalone system equipped with its individual programmable logic controller (PLC) to control the functionality. Cold box consists of total 8 heat exchangers and 3 turboexpanders and 1 JT valve. The HRL process is a modified claude cycle and is specifically tuned for SCMS operation. Temperature, mass flow rate and effectiveness are main process parameters of heat exchanger. Process parameters for turboexpander are temperature, mass flow rate, pressure and efficiency that has to be optimized for getting maximum liquefaction at minimum refrigeration load. An oil injected screw compressor compresses pure helium gas from atmospheric pressure (1.05 bar) to approximately 14 bar (depending on the chosen compressor).A water cooler or an air cooler is used to remove the heat of the compression.To prevent the contamination of liquefier an oil removal system (ORS) is used to remove the residual oil in Helium gas. Oil is removed in subsequent stages with the help of bulk oil separators, 3 coalescers and a charcoal adsorber.

Pure high pressure helium gas is fed to cold box (CB). The heat exchangers HX-1 to HX-5 together with the turboexpanders A and B are connected in series, providing pre-cooling for the downstream flow of helium, while J-T valves provides cooling effects at the cold end of cold box as shown in fig.1. HX-1 and LN2 HE are used to cool the main process stream from 300 K to 80 K with help of liquid nitrogen (LN2). Turboexpanders A and B reduces the temperature from about 35 K to 15.5 K by diverting the moderate flow from the total flow of compressor. The heat exchangers HX-6 and HX-7 combining with return cool flow from main control Dewar (MCD) reduces the temperature of downstream helium flow up to 6 K. After this the Turboexpander C between these heat exchangers(HX-6 and HX-7) is operated and the temperature further comes down to about 5.3 K. And at last the J-T valve performs the isenthalpic expansion and producing the liquid- vapor mixture and finally two-phase fluid is separated in the MCD. Liquid helium is obtained at 1.2bars and 4.5K in the MCD. Cold helium gas from the MCD through the cold box low pressure return stream to the compressor suction forms the closed loop as a refrigerator. If the liquid is used for the application as in SCMS then it forms the liquefaction mode[2].

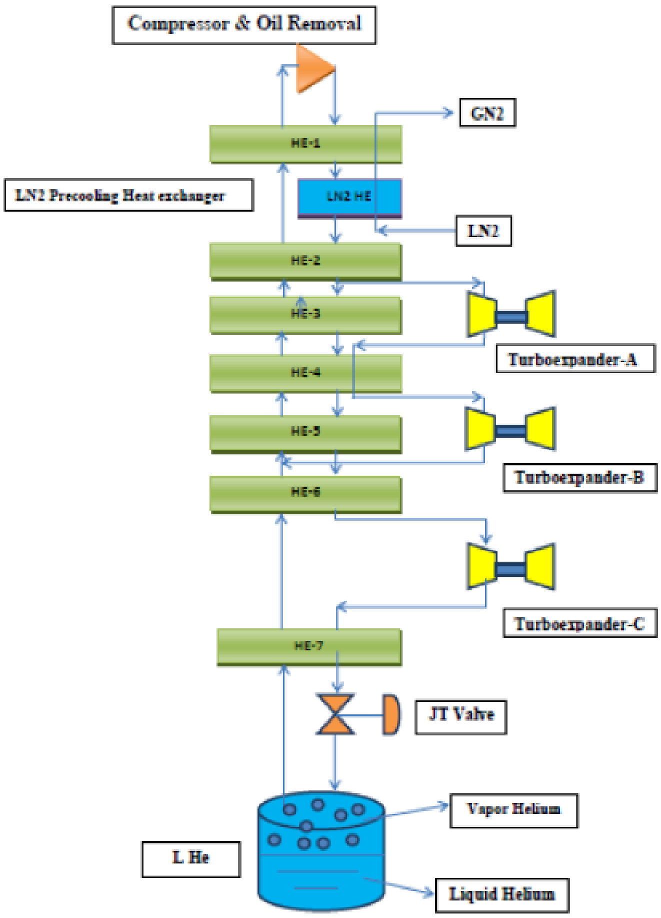


Figure 1.1: Process Flow Diagram of HRL

1.3 Project Objective

Liquid helium at 4.5K is the prime requirement of the plant. The major component is CORS System and coldbox. The main objective of the project is to

- Study the existing control system architecture and logic of CORS system available in IPR.
- Develop a control system logic for CORS to operate the valves in different operational scenario so as to match input and output pressure at specified limit(1.05 bar at suction and 14 bar at discharge of compressor).
- Make MIMIC diagram in SCADA. Interface of data loggers, scanners and Siemens PLC with the SCADA.
- Documentation for the above work.

1.4 Thesis Organization

The rest of the thesis is organized as follows.
In chapter 2, various literature are reviewed in order to understand the plant and cryogenics involved. The thermodynamics behind the process is understood. Sensors and

control mechanisms involved are also studied and discussed.
In chapter 3, CORS system is addressed in detail. Its different components, their requirement is discussed and control problem is well defined.
Chapter 4 discusses about system analysis using aspen HYSYS and tool is explored for model identification. Chapter 5 gives insight to a platform on which logic is developed which is step7 and wincc exible by Siemens. SCADA mimic is developed in wincc flexible. Control solution is described and simulation results are produced. Then thesis is wound up with conclusion and future scope.

Chapter 2

Literature Survey

2.1 The Helium Potential Of India

Helium is most abundant element but scarce in earths atmosphere because of its thermal diffusion to outer space. Helium finds its application involving space, superconductivity, atomic energy and in many advanced researches, including fusion and behaviour of materials at very low temperatures. Remarkable application of liquid helium is as a refrigerant for superconducting magnets, used for superconducting cyclotron[3].

Due to very low abundance of helium (approx.5.2 ppm) in atmosphere, it is energywise uneconomical for large-scale extraction from this source. It has been the case that 90% of helium-rich natural gas reserves are concentrated in North America.The world production and reserve base of helium is given in fig.2.1.

Country	Production (MCM)	Reserve base (BCM)
USA	87.0	8.9
Algeria	17.0	3.0
Canada	NA	2.0
China	NA	1.1
Poland	1.0	0.28
Russia	4.0	6.7

MCM, Million cubic metre; BCM, Billion cubic metre.

Figure 2.1: World production and reserve base of helium

Since natural gas deposits are not found in India, we have to look for it in unconventional sources such as thermal spring and monazite sands. There are nearly 300 thermal springs all over India. Preliminary estimation performed by Variable Energy Cyclotron Centre (VECC), Department of Atomic Energy (DAE) at Bakreswar, West Bengal reveals that thermal springs emit natural gases containing helium in significant measure. Three distinct belts of thermal springs so far identified in India by the Geological Survey of India are: (1) West coast of India Thane, Ratnagiri, Colaba and Surat,(2) Eastern India Assam, Bihar, and Orissa; and (3) Himalayan Belt Gangotri, Jamunotri (Uttaranchal) and Monikaran (Kullu Valley, Himachal Pradesh).

In India, such efforts to extract Grade-A helium from this natural gas have not yet started. It is high time that we should make serious efforts to extract helium from available natural gas sources and become self-reliant in Grade-A helium. The expertise outlined here gives the growing demand of cryogenic technology in our country[4].

2.2 Basics Of Refrigeration

2.2.1 Isentropic Compression/Expansion

Derivation of two important equations which gives relation between pressure, temperature, and volume which a gas occupies during reversible compression or expansion is explained here.

From specific heat coefficient's definition, the specific heat at constant pressure Cp minus the specific heat at constant volume Cv is equal to the gas constant R:
Specific Heat: The amount of heat required to raise the temperature to 1 unit.
Cp=specific heat at constant P
Cv=specific heat at constant V
R=Gas Constant=Cp-Cv...(1)
gamma = Cp / Cv

If we divide the 1st eq. by cp, and use the definition of "gamma" we obtain:

R / cp = 1 - (1 / gamma) = (gamma - 1) / gamma

Now using the equation for the entropy of a gas:

s2 - s1 = Cp ln(T2 / T1) - R ln(p2 / p1)

where the numbers 1 and 2 denote the states at the beginning and end of the compression process, s is the entropy, T is the temperature, p is the pressure, and "ln" denotes the natural logarithm function. Since there is no heat transferred into the cylinder and no other losses, the change in entropy is zero. Then the equation becomes:

Cp ln(T2 / T1) = R ln(p2 / p1)

Dividing both sides by "Cp" and taking the exponential function of both sides (this "un-does" the logarithms).

ln(T2 / T1) = (R/Cp) ln(p2 / p1)

T2/T1=exp[(R/Cp)ln(P2/P1)]

In compression process, when the pressure is increased from p1 to p2, temperature increases from T1 to T2 according to the exponential equation. "Gamma" is a quantity which depends on the gas. For air, at STP, it is 1.4. So if the pressure is doubled, the temperature is increased by a factor of 1.219. we have a function which relates tem-

T2 / T1 = (p2 / p1) ^ (R / cp)

where the symbol "^" denotes an exponent. Now we substitute the expression for "R / cp" to obtain:

$$\boxed{T2 / T1 = (p2 / p1) \wedge [(gamma - 1)/gamma]}$$

perature change to the pressure change during a compression process. We can use the equation of state to derive the relation between the pressure change and volume change. The equation of state is:

p * v = R * T

where v is the specific volume occupied by the gas. substituting this expression for T into the temperature equation, we obtain:

(p2 * v2) / (p1 * v1) = (p2 / p1) ^ [(gamma - 1)/gamma]

Multiply both sides by (p1 / p2) to get:

v2 / v1 = (p2 / p1) ^ (- 1/gamma)

$$\boxed{P2/p1 = (v1/v2) \wedge gamma}$$

The quantity (v1/v2) is called the compression ratio. For v2 less than v1, the pressure p2 is greater than p1. Compression ratio is a function of the design of the bore and stroke of the piston.[5]

2.2.2 Second Law Of Thermodynamics

Heat flows from high temperature to low temperature.The second law states that to pump the heat from low temperature to high temperature the work is required. so, work input is required to generate and maintain low temperatures.[6]

2.2.3 JouleThomson Coefficient

The JouleThomson (or JT) coefficient is slope at any point of an isenthalpic curve on a temperaturepressure diagram. The JT coefficient is usually denoted by u(mu) and is given by

$$\mu = (dT/dP)H$$

The locus of all points at which the JT coefficient is zero is known as the inversion curve and is shown as a dotted curve in fig 2.2. The region to the left of the inversion curve, where the JT coefficient is positive, is the region of cooling; the region where the JT coefficient is negative, is the region of heating.

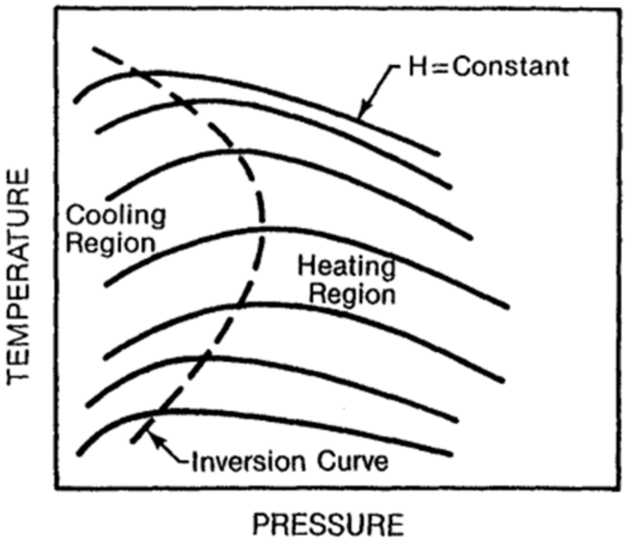


Figure 2.2: Joule-thomson inversion curve

Hydrogen, helium, and neon have negative JT coefficients at ambient temperature. Hence, when used as refrigerants in a throttling process, they must be cooled either by a separate precoolant fluid or by a work-producing expansion to a temperature below which the JT coefficient is positive. Then only throttling will cause a further cooling rather than heating.

- J-T expansion is called isenthalpic. In similar manner when gases are expanded at constant entropy, it is called isentropic expansion.
- As in the case JT effect ujt=0, the isentropic expansion coefficient us $\neq 0$.

- Means ideal gas does exhibit cooling effect ,when it undergoes isentropic expansion.[6]

2.3 Liquefaction and Refrigeration Cycle

Thermodynamically Ideal System, Linde-hampson system, Precooled linde hampson system, Linde dual pressure system, Claude system, Kapitza system, Heylandt system and Collins system are the liquefaction and refrigeration system cycles which are ivolved over time with modification from one to other so as to increase efficiency and liquid yield with optimizing the power requirement.

The work required per unit mass of gas compressed and liquified by thermodynamically ideal system is given by

(-Wc)/mf=T1(s1-sf)-(h1-hf)...(2)

Where, negative sign is because work is done on the system and T1 represents initial temperature of the gas, subscript f is for final condition, s and h represents entropy and enthalpy respectively. From eq.2 we can say that work requirement is dependent on the initial condition of the gas. To liquefy a gas using ideal system the required pressure at the end of compression is very high approx. thousand bar for N2. Such high pressure is very impractical so there is a need to modify a system to lower the maximum pressure. Devices like JT valve, expansion engines and heat exchangers are used to modify a system[6].

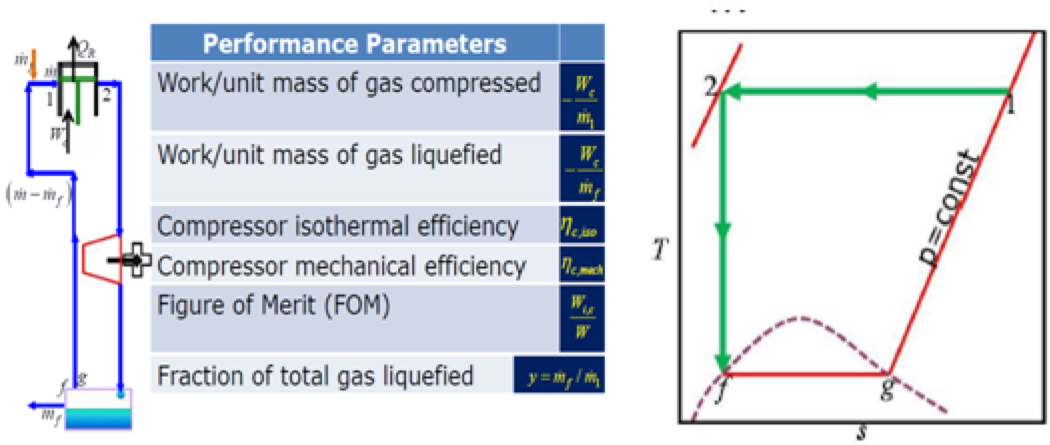


Figure 2.3: Gas liquefaction parameters

In liquefaction system, ideal system is used as a benchmark to compare the performances of different cycle as shown in fig.2.3. The fraction of gas liquefied or liquid yield is given by,

$$\frac{\dot{m}f}{\dot{m}} = y = \frac{(h1 - h2)}{(h1 - hf)}$$

Where, subscript 2 is point at discharge of compressor In order to obtain maximum yield, the value of h2 should be as small as possible. In order to maximize y, the state 2 should lie on the inversion curve for a particular gas at the temperature of compression process. In linde-hampson cycle heat exchanger and JT valve is used. Following hold true for linde cycle. As compression pressure increases and temperature decreases, the yield y increases at a given temperature and pressure. So to obtain maximum yield subsequent cycles are invented which will try to decrease compression temperature and increase compressor pressure[6].

In 1920,claude developed an air liquefaction system and established Air Liquide.

It is based on the idea that in order to achieve better efficiency the expansion process should be reversible process. So to do that expansion engine is used as JT valve gives irreversible isenthalpic expansion. And for any gas, reversible isentropic expansion gives lower temperature irrespective of its inversion temperature.

The schematic is given in fig.2.4. it has a compressor,3 HXs,1 JT valve and also have one expansion device operated between second heat exchanger as shown in fig.4. The energy content in the gas is removed by allowing it to do some work in an expansion device.

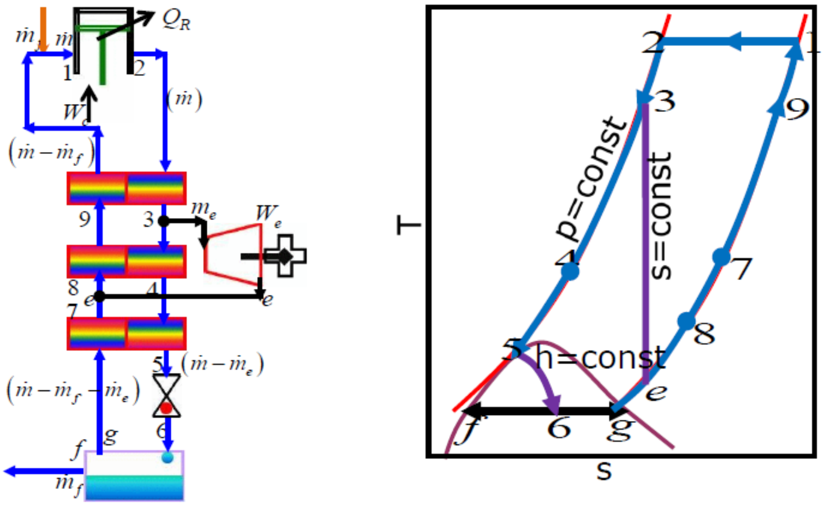


Figure 2.4: Schematic of claude cycle with T-S diagram

As shown in fig.2.4. a part of the main stream of the gas is expanded from 3 to e and it is reunited with the return stream. This process of expansion is known as reversible adiabatic expansion[6,7].

2.4 Diodes As Temperature Sensor

The forward voltage of a semiconductor junction at a constant current is a well-defined function of temperature and has been widely used for over 40 years to measure temperature in the range 1400K (Rao, 1982). The forward voltage temperature characteristics (VTC) of semiconductors like germanium, gallium arsenide, and silicon junctions have been investigated extensively over the last two decades or so. The silicon diode is currently most widely used sensor, as being the most stable and reproducible. Diodes are more sensitive and more nearly linear over more of their usable range than carbon, germanium, and platinum RTs. Their biggest advantage is unquestionably the wide temperature range over which reasonable resolution is maintained, perhaps 10mK over the 2 - 300K range.

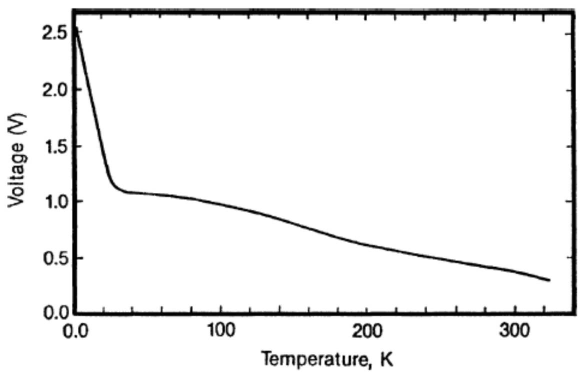


Figure 2.5: Voltagetemperature curve for a typical silicon diode temperature sensor at a constant current of 107 mA. (Courtesy of LakeShore Cryotronics Inc., Westerville, OH.)

There are several significant measurement advantages in using diodes instead of resistance thermometry or thermocouples. As the signal level is on the order of a volt and sensitivities are quite large, thermal emfs are not a significant source of temperature uncertainty. Also, because the diode gives an absolute measurement, reference baths or reference junctions are not required. Constant-current operation avoids the necessity of a variable current source as in the case of resistance thermometry, and the wide range of the diode sensor eliminates the need for multiple sensors. These reasons, combined with the ability to select diodes that follow standardized calibration curves, make the diode an excellent choice for use in temperature controllers and other instrumentation[8].

2.5 Compressor With Surge Avoidance Control

In centrifugal compressor system surge is an undesirable and unstable condition, which occurs at specific combination of discharge pressure and volume flow in compressor. In such condition, flow will be reversed and if not controlled, results in mechanical damage of the compressor. This can be avoided by variable speed control, suction throttling, adjustable inlet guide vanes and bypass throttling. Among which the simplest solution is to recycle the flow from discharge to suction so that compressor can operate within its range of stability. In fig.2.6, volume flow versus discharge pressure is plotted where we can see a constant speed lines on which at a specific flow- head combinations, flow rate minimization is accompanied with lowered discharge pressure and at that point, flow in the compressor will be reversed. Lines connecting this points is called a surge line[9].

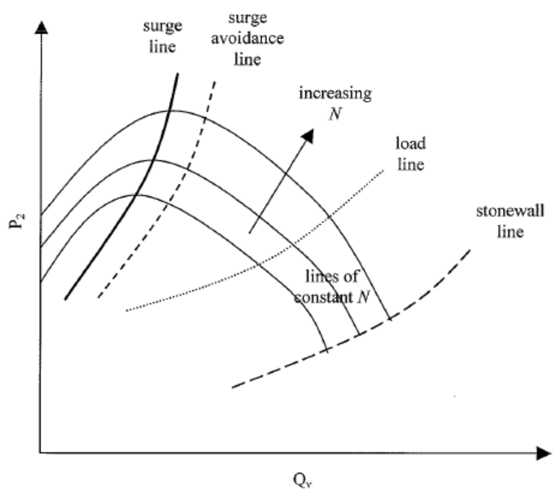


Figure 2.6: Schematic representation of a compressor map.

2.5.1 Anti Surge Control Valve

The anti surge valve can be fail open solenoid valve. That means that it needs a high signal of 20 mA to close the valve, and a low signal of 4 mA to open the valve. When failure occurs, the valve will usually receive a low signal and it will open, which is the safe position. When opened, it directs the pressurized fluid from compressor discharge to suction of the compressor. This prevents the flow from becoming too low at the compressor inlet[10].

2.6 Development Of Critical Components For Cryogenic Systems

2.6.1 Cryogenic Turboexpanders

Turboexpanders, being the active cooling component of modern plants are considered the heart of the system. The mixed-flow turbines rotate extracting energy from the high pressure process stream thereby inducing the cooling. Cryogenic conditions necessitate the use of smaller gas passages in the turbines that translate into small size and correspondingly high speed for high operational efficiency. They are designed to achieve a speed of around 2,40,000 r/min, have already been developed and tested in existing plants with satisfactory performance.

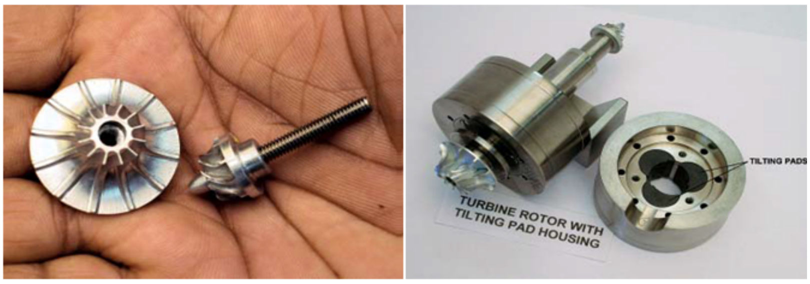


Figure 2.7: Miniature turbomachinery: expansion turbine and brake wheel

operational efficiency of the system presents typical problems of radial bearing instability. Tilting pad journal bearings consisting of three pads per bearing and possessing excellent stability characteristics constitute the journal bearing system. The entire bearing system is designed to provide enough damping to cross over critical speeds easily.

2.6.2 Cryogenic Heat Exchangers

High effectiveness (in excess of 0.95) brazed plate and fin heat exchangers are a necessity for modern high performance cryogenic plants. As the technology for these exchangers (fins, large brazing furnaces, transition joints, etc) is not available in India, Cryogenic Technology Division has undertaken development of these components. In a transition joint between aluminium and SS 304 pipes using diffusion bonding techniques have been fabricated at the Centre for Design and Manufacture, BARC. The joint withstood a full vacuum and pressure holding of 30 bar. As a step towards the future development, high effectiveness (0.97 or higher) matrix type heat exchangers, which are used in small cryo coolers, have been designed.

2.6.3 Accessories for Cryogenic Systems

Most valves used in cryogenic processes need extended stem with thin wall to serve the following primary purposes:
a) The valve handle is maintained at ambient temperature to protect the operator (whether operated manually, pneumatically, or by solenoid)

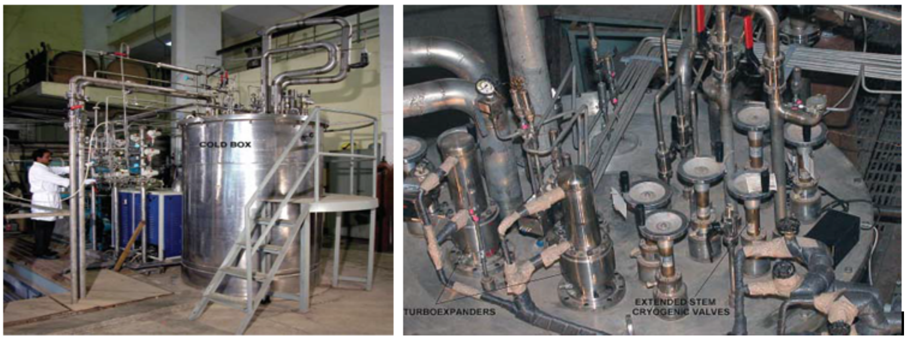


Figure 2.8: The prototype 1kW at 20K Cryogenic Refrigeration system developed and installed at BARC(left).A close-up of the prototype refrigeration system showing turboexpanders, extended stem valves, and external piping mounted on the top cover of the cold box(right)

b) The valve stem may be sealed at ambient temperatures instead of cryogenic temperatures, thereby eliminating a severe sealing problem and improving the reliability of the valve, and
c) In order to prevent a loss of cold from process to environment. Special long stem bellow seal cryogenic valves have been developed for use in the proposed helium liquefier[11].

Chapter 3

Compressor And Oil Removal System

3.1 Requirement Of Compressor & Oil Removal System For The Helium Plant

The main aim of helium liquefier is to produce pure liquid helium. So to produce that liquid helium, gaseous helium should be expanded. Expansion process can be carried out two ways, isentropic and isenthalpic. In both process, pressure as well as temperature of helium gas goes down. During isentropic expansion, energy is removed from the gas as external work so it called external work method and in isenthalpic expansion, expansion valve does not remove energy from the gas but moves the molecules farther apart under the influence of intermolecular forces so it called internal work method. It appears that expanding the gas through expander always be the most effective means of lowering the temperature. Helium cannot be expanded directly at the atmospheric condition. To expand helium, first it should be compressed up to optimum level, therefore efficient compressor system is the essential part of helium liquefier. Due to the properties of helium, its compression is accompanied by a high temperature rise.

As discussed earlier, Temperature and pressure is related by equation

$$T2 / T1 = (p2 / p1) ^\wedge [(gamma - 1)/gamma]$$

Now, gamma=1.66 for Helium

So,(14)^[(1.66-1)/1.66]=T2/T1=2.8

T1=27+273=300K

So, T2=2.8*300=840K

A pressure ratio of 14 would be an ideal isentropic compression process, generate a temperature ratio of 2.8, i.e. the helium temperature would rise up to 840 K. So oil is used to take up some heat of compression and try to achieve isothermal compression and decreases the compression work. But the disadvantage of oil in contact with the helium is, it creates an undesired contamination of the gas. The oil must therefore be removed by a series of coalescing filters and a final adsorber bed with activated charcoal filling. The compressor suction pressure is decided based on the LHe Dewar pressure and pressure drop along the path between this Dewar and Compressor suction. The pressure in the LHe Dewar is decided based on the cooling temperature required in the application. Normally the LHe Dewar pressure is kept above atmospheric pressure so that suction helium pressure at the compressor is also above atmospheric pressure to prevent the leakage into the system. The PFD of CORS is given in fig.3.1.[12]

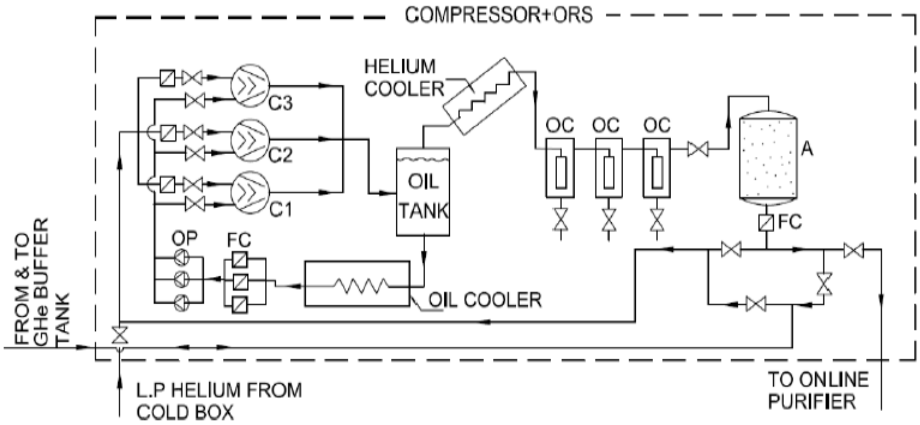


Figure 3.1: Process Flow diagram of CORS

3.2 Operational Scenario of CORS

Compressor and oil removal system is planned to have three compressors and each compressors will have flow rate of 70 g/sec and 14.8 bar pressure at the outlet of the compressor. Allowable pressure drop through CORS (oil tank, helium cooler, coalescers, adsorber bed, filter, valves, piping) is 0.8 bar so the pressure at the outlet of the CORS is 14 bar and total mass flow rate is 140 g/sec. Helium gas is just above atmospheric pressure 1.05 to 1.0 bar and atmospheric temperature passed to the upstream of the compressors from the cold box. Sometimes helium gas is taken from the buffer tank during the start up the compressors. For the operational design and understanding point of view only one compressor with the oil removing system is considered. P & ID of CORS is shown in appendix. Power supply to the compressor is from the three phase induction motor. Induction motor of the compressor can be operated using speed control with variable frequency drive or slide valve control or at the constant speed.

At inlet of compressors, high pressure oil at 18 bar pressure from oil pump need to be supplied to the bearings and drive shaft for the support load due to rotors and shaft weight. It is expected that 3 oil pumps will be required considering exibility and redundancy in operation. Helium is compressed after mixed with oil in the helium compressor. In case of the helium, due to the high specific heat ratios, isentropic compression leads to high temperature rise and consequently high compression work compared to other gases. Oil, which has high specific heat (low temperature rise with high heat load) is sprayed and mixed with helium gas at the suction chamber and then compressed. Most of the compression heating is absorbed by the oil and temperature rise is reduced significantly and hence also the compression load is reduced. This process approaches to isothermal compression. This oil works as lubrication and sealing between casing, rotor and stator also. This also helps to reduce helium leakage to atmosphere from compressor. After compression, mixture of oil and helium at 80 to 100 C and 14.8 bar goes to an oil tank or oil separator where helium goes out at the top of it and passes to a helium cooler at the pressure 14.6 bar and temperature 90 C. Helium cooler is use to cool the helium gas to 25 C through water. Allowable pressure drop through the helium cooler is about 50 to 100 mbar. Some part of oil vapor, carried through the helium gas, gets condensed and comes down to the tank due to gravity and slanted position of this helium cooler. Still some oil vapor remains in the helium gas, which is coalesced in the coalesce cum- filters kept in the downstream of the helium cooler.

It is expected that 4 coalescers connected in series are used to remove oil from helium to about 10 PPM level. Allowable maximum pressure drop through four coalescers are about 200 mbar. This helium will be further passed to the charcoal bed for remaining oil vapor adsorption. The oil content in the helium gas after adsorber bed is about 1 PPM level. This helium gas further passed through a filter cartridge to remove charcoal dust particles comes with helium gas from charcoal bed. This high pressure and purified helium gas is passed to the online purifier or to the cold box. Allowable maximum pressure drop through the adsorber bed and charcoal dust filter are about 100 mbar and 50 mbar respectively. After the charcoal dust filter cartridge, there is a provision to transfer excess helium to the buffer tank through a pressure control valve. Generally Buffer tank pressure is kept at about 13 bar or less. Downstream of this charcoal dust filter cartridge, there is also a provision for by-pass of this pressurized helium through a pressure control valve to take it to the suction of the compressor instead of going to the cold box.

This is needed when cold box helium path is isolated from the compressor system at the start of the helium plant operation. Sometimes this is required for checking of compressor operation stability before connection to the cold box helium path. If helium is needed from buffer tank, through a pressure control valve, it goes to the suction line and joins at the downstream of the by-pass pressure control valve. Oil will be taken out from the bottom of the oil tank or oil separator is about 90 0C temperature and it will be cooled through water cooled oil cooler to about 30 0C, which then will go to oil pump through oil filters. At the suction of this oil pump, pressure could be about 13 bar and at the outlet it could be about 18 bar. This oil is then circulated to the compressor. It is expected that 3 oil pumps will be required considering exibility and redundancy in operation. Some amount of oil from oil coalescers is returned to compressors, also some amount of oil from oil tank is also returned to the compressors[12].

3.3 Compressor

As the main component of CORS system is compressor and plant overall efficiency is dependent on the performance of compressor, it is discussed here briefly. Most of Compressors are specified with following parameters: 1) Mass Flow Capacity 2) Inlet or Suction Pressure 3) Discharge or Operating Pressure 4) Inlet Temperature 5) Speed 6) Type and Volume of gas handled.

There are two basic compressor types: positive-displacement and dynamic.

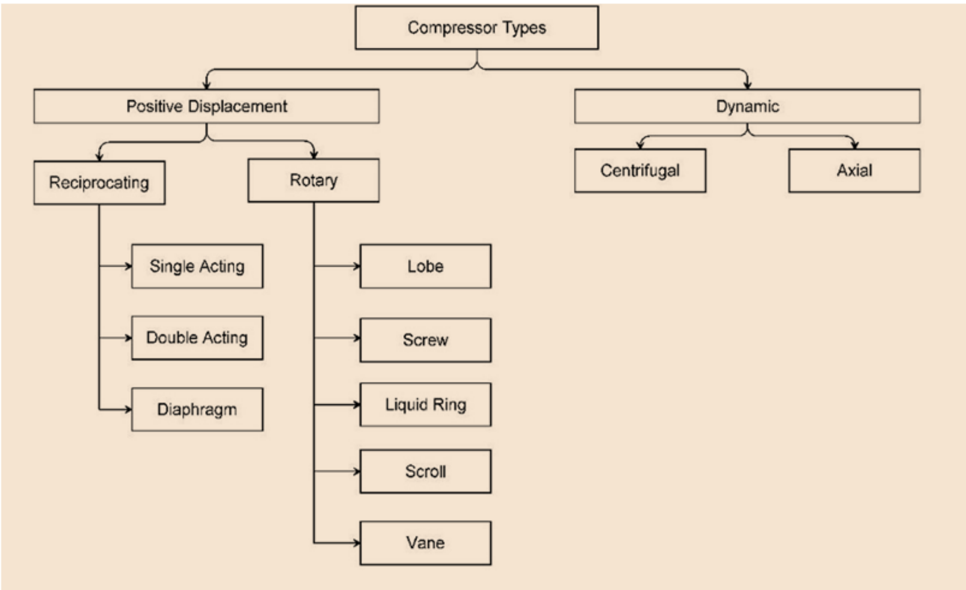


Figure 3.2: Compressor Classification

1. In the positive-displacement type, a given quantity of air or gas is trapped in a compression chamber and the volume it occupies is mechanically reduced, causing a corresponding rise in pressure prior to discharge. At constant speed, the air flow remains essentially constant with variations in discharge pressure.
2. Dynamic compressors impart velocity energy to continuously owing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers. In the centrifugal-type dynamic compressors, the shape of the impeller blades determines the relationship between air flow and the pressure (or head) generated. In HRL plant at IPR screw compressor is used.

The rotary screw compressors can be either twin-screw type or single-screw type.

3.3.1 Twin-screw compressor

The twin-screw type compressor consists of two matching helically grooved rotors, one male and the other female. Generally the male rotor drives the female rotor. The male rotor has lobes, while the female rotor has flutes or gullies. The frequently used lobe-gully combinations are [4,6], [5,6] and [5,7]. fig.3.3 shows the [4,6] combination. For this [4,6] combination, when the male rotor rotates at 3600 RPM, the female rotor rotates at 2400 RPM. As shown in fig.3.3, the flow is mainly in the axial direction. Suction and compression take place as the rotors unmesh and mesh. When one lobe-gully combination begins to unmesh the opposite lobe-gully combination begins to mesh. With 4 male lobes rotating at 3600 RPM, 4 interlobe volums are per revolution, thus giving 4 X 3600 = 14400 discharges per minute[13].

Discharge takes place at a point decided by the designed built-in volume ratio, which depends entirely on the location of the delivery port and geometry of the compressor.

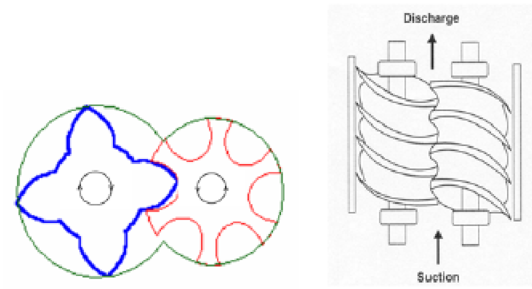


Figure 3.3: Twin-screw compressor with 4 male lobes and 6 female gullies and Direction of refrigerant flow in a twin-screw compressor

Since the built-in volume ratio is fixed by the geometry, a particular compressor is designed for a particular built-in pressure ratio. However, different built-in ratios can be obtained by changing the position of the discharge port. The built-in pressure ratio, rp given by:

rp=Pd/Ps=Vb^k

Where Pd and Ps are the discharge and suction pressures, Vb is the built-in volume ratio and k is the index of compression. If the built-in pressure at the end of compression is less than the condensing pressure, high pressure refrigerant from discharge manifold flows back into the interlobe space when the discharge port is uncovered. This is called as undercompression. On the other hand, if the built-in pressure at the end of compression is higher than the condensing pressure, then the compressed refrigerant rushes out in an unrestrained expansion as soon as the port is uncovered (over-compression). Both under-compression and over-compression are undesirable as they lead to loss in efficiency.

Figure 3.4: Cutaway drawing of a twin-screw compressor

Lubrication and sealing between the rotors is obtained by injecting lubricating oil between the rotors. The oil also helps in cooling the compressor, as a result very high pressure ratios (upto 20:1) are possible without overheating the compressor. Fig.3.5. shows the compression efficiency of a twin-screw compressor as a function of pressure ratio and built-in volume ratio. It can be seen that for a given built-in volume ratio, the efficiency reaches a peak at a particular optimum pressure ratio. The value of this optimum pressure ratio increases with built-in volume ratio as shown in the figure. If the design condition corresponds to the optimum pressure ratio, then the compression efficiency drops as the system operates at off-design conditions. However, when operated at the optimum pressure ratio, the efficiency is much higher than other types of compressors.

As the rotor normally rotates at high speeds, screw compressors can handle fairly large amounts of refrigerant flow rates compared to other positive displacement type compressors. Screw compressors are available in the capacity range of 70 to 4600 kW. They generally compete with high capacity reciprocating compressors and low capacity centrifugal compressors. They are available for a wide variety of refrigerants and applications. Compared to reciprocating compressors, screw compressors are balanced and hence do not suffer from vibration problems.

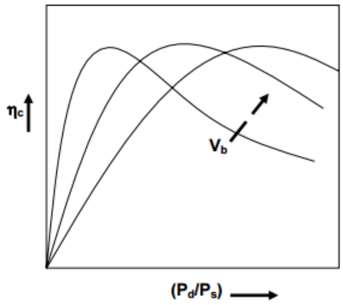


Figure 3.5: Variation of compression efficiency of a twin-screw compressor with pressure ratio and built-in volume ratio

Twin-screw compressors are rugged and are shown to be more reliable than reciprocating compressors; they are shown to run for 30000 to 40000 hours between major overhauls. They are compact compared to reciprocating compressors in the high capacity range[13].

3.4 Oil type

The use of synthetic polyglycol oil is widely spread in cryogenic Warm Compression Stations due to:
1)High lubricating properties
2)Good viscosity/temperature ratio
3)Low vapor pressure at the operating temperature (essential for cryogenic application)
As required oil, BP BREOX B35 could be used for screw compressor lubrication and BP BREOX IL 150 SW could be used for reciprocating compressors[14].

3.5 Control Valves and Actuators

The control action in any control loop system, is executed by the final control element. Thus the effectiveness of any control scheme depends heavily on the performance of the control valve. The proper design and fabrication of the valve is very important in order to achieve the desired performance level. The most common type of final control element used in process control is the control valve. A control valve is normally driven by a diaphragm type pneumatic actuator that throttles the flow of the manipulating variable for obtaining the desired control action. A control valve essentially consists of a plug and a stem. The stem can be raised or lowered by air pressure and the plug changes the effective area of an orifice in the flow path. A typical control valve action can be explained using Fig.3.6. When the air pressure increases, the downward force of the diaphragm moves the stem downward against the spring.

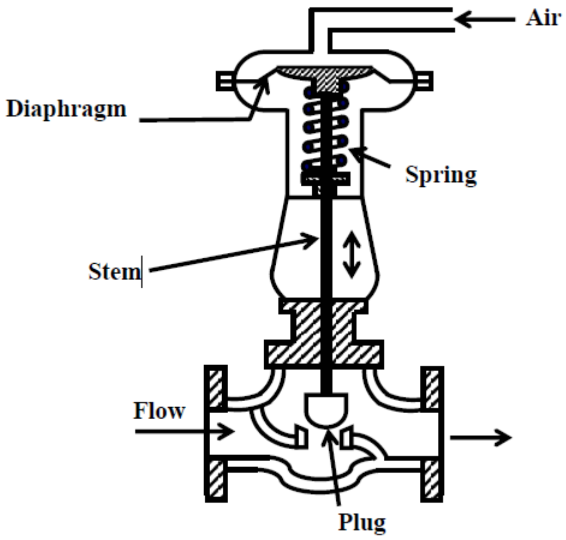


Figure 3.6: A schematic of a control valve

Classification of Control valves

Control valves are available in different types and shapes. They can be classified in different ways; based on: (a) action, (b) number of plugs, and (c) flow characteristics. According to action it can be air-to-open or air-to-close. According to number of plugs, valves are characterized as single seated or double seated. The important is flow characteristics which describe flow rate changes with movement of stem which is decided by shape of plug. Valves exhibit inherent characteristics which is dependent on shape and size of plug and effective flow characteristics when it is connected between pipelines.

Ideal valve characteristics is given by,

$$Q = K1a\sqrt{2g(h1 - h2)}$$

Where,
Q = flow rate in m3/sec
K1 = The flow coefficient also called Cv, is the volume (in US gallons) of water at 60F that will flow per minute through a valve with a pressure drop of 1 psi across the valve.
a = area of the control valve opening in m2
h1 = upstream static head of the fluid in m
h2 = downstream static head of the fluid in m
g = acceleration due to gravity in m/sec2.
Keeping upstream and downstream head constant we get Q=f(z). z is a stem lift which will decide plug area. The characteristics of these control valves are shown in fig.3.7. It has to be kept in mind that all the characteristics are to be determined after maintaining constant pressure difference across the valve as shown in Fig.3.7.

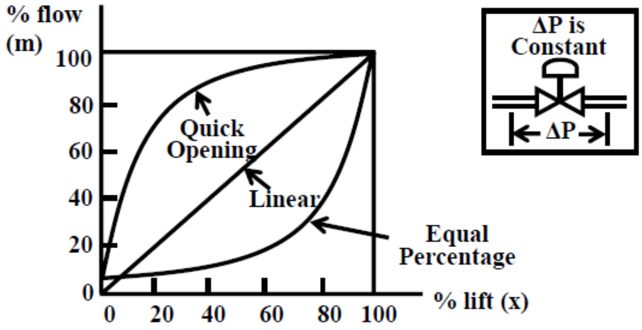


Figure 3.7: control valve ideal characteristics

Rangeability of a control valve is defined as the ratio of the maximum controllable flow and the minimum controllable flow. It is between 20 and 70 generally.[15]

3.6 Control Problem and Solution

In HRL plant at IPR, compressor station consists of two screw compressors installed in parallel between 1.05 and 14 bars with a maximum flow of 70 g.s-1 as shown in fig 3.8. The system contains three control valves. The bypass valve (CV956) sets the suction pressure of compressor. It is used to pass the flow that the cold box cannot accept. The CV952 and CV953 valves are used respectively to supply or remove gas from the system via a helium gas drum. Pt is the tank pressure[16]. The project work mainly includes to

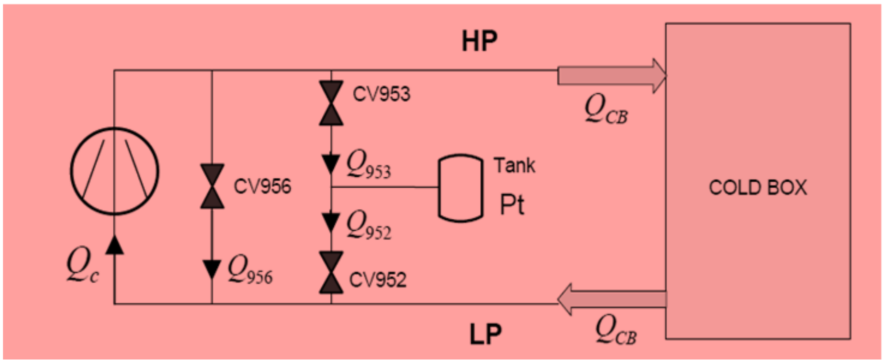


Figure 3.8: Warm compression station

develop a logic for this control problem and test it with PLC and also simulate compressor performance with modeling tool like aspen HYSYS.

So, to solve this problem and maintain compressor inlet and outlet pressure at specified limit we can use two Proportional/Integral/Derivative (PID) controllers. The first PID manipulates the by-pass valve to regulate the LP at 1.05 bars. The CV952 and CV953 valves can be arranged in the split range configuration (fig 3.10). So,if the discharge pressure is greater than 14 bar we want to open buffer inlet valve (discharge extra helium in buffer tank) and when discharge pressure less than 14 bar then we want to open buffer outlet valve(charge to fill extra helium) and control the HP at 14 bars with the constraint that both cannot operate simultaneously. All the valves are equal percentage and their rangeability is 50%.

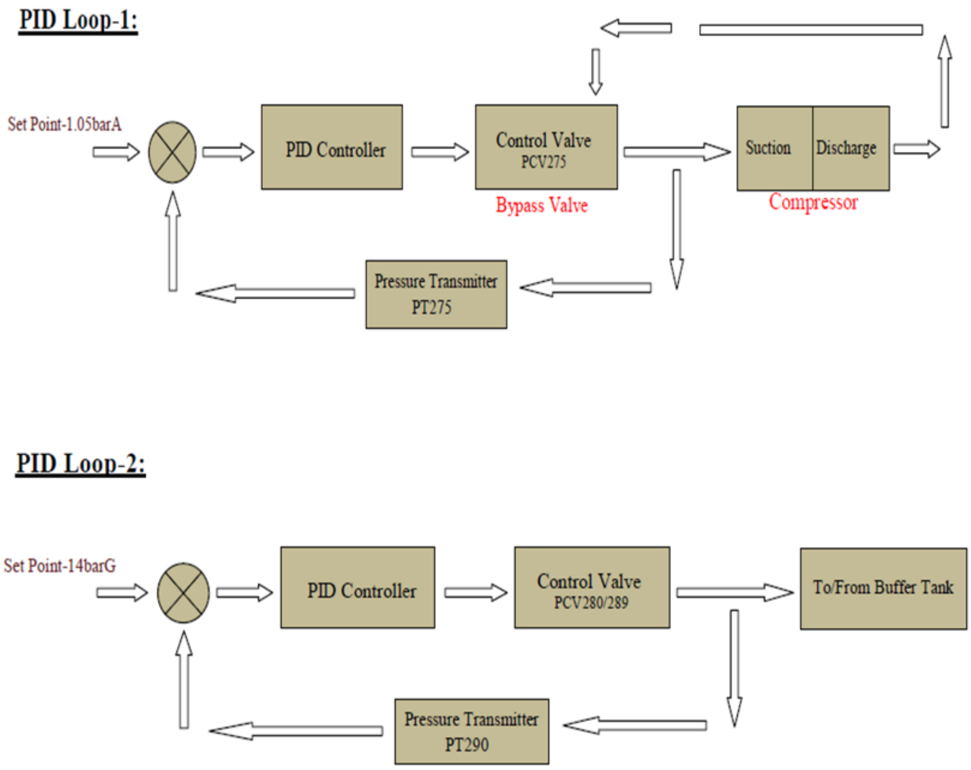


Figure 3.9: PID loops for closed loop control

PID Loop-1

This loop maintains the compressor suction pressure at 1.05barA otherwise pressure at suction goes down to atmospheric pressure that is vacuum which is not recommended for compressor safe operation.

PID Loop-2

During start up Compressor needs continuous gas supply source till it attains set pressure (14barG). In our application buffer tank full fills that requirement and gas would be sends to buffer tank, if pressure at discharge side exceeds set limit. So, this PID control loop take cares the rate of opening and closing of gas supply and gas Intake valves. Both the loops are shown in figure 3.9.

3.6.1 Split Range Control Scheme

As shown in figure 3.10, when PV ranges from 0 to 20 bar, controller will give output from 0 to 100% means 4 to 20 mA. Implementing split range control needs to decide splitting point and splitting configuration. In present problem, while configuring this scheme we have to consider so many parameters like valve characteristics, valve stickiness factor, dynamic model etc. to get exact output. From the problem when starting compressor, it will start developing pressure from 0 to 1,2,3.bar. We want discharge pressure as 14 bar. So initially compressor will take gas from buffer tank. From buffer tank valve must be closed when PV reaches to 14 bar. But if it starts closing at 14 then due to valve

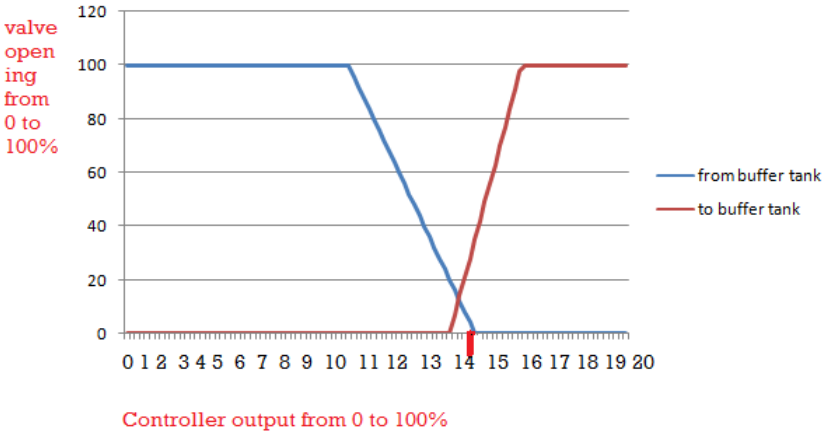


Figure 3.10: Split range control

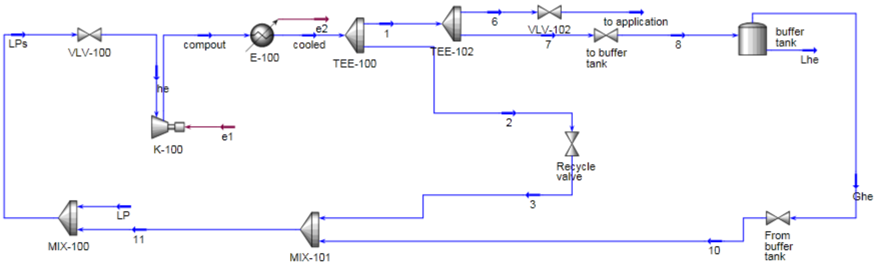
stickiness factor it will take effect after some time and pressure will increase from 14 bar. So, we must start closing this valve when PV=9 bar. Same thing with to buffer tank valve will apply. So, we must start opening it prior it will reach to 14 bar. This zone entirely depends on valve characteristics.

Chapter 4

Simulation with Aspen HYSYS

Aspen HYSYS is a powerful engineering simulation tool for process modeling with strong thermodynamic foundation[17]. We can simulate almost all processes with aspen HYSYS. HYSYS provides so many functionality for simulation as such steady state analysis, dynamic analysis, report generation, property viewing, strip charts, event management and so on. Building a simulation in HYSYS is followed by following steps:

1)Select component to model.
2)Select appropriate fluid package: The fluid package contains all the necessary information for pure component flash and physical property calculations. This allows you to define all the required information inside a single entity.
3) Build a flow sheet consisting of material streams and all unit operation with defined parameters.
4)see results[18].
Here, simulation is done for helium gas, fluid package selected is peng- robinson.



Energy Streams			
		e1	e2
Heat Flow	kW	264.3	264.4

Material Streams									
		he	compout	cooled	LPs	1	2	3	6
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Temperature	K	300.0	1027	300.0	300.0	300.0	300.0	299.8	300.0
Pressure	bar	1.050	14.00	13.50	1.300	13.50	13.50	1.300	13.50
Molar Flow	kgmole/h	62.95	62.95	62.95	62.95	31.48	31.48	31.48	15.74
Mass Flow	g/s	70.00	70.00	70.00	70.00	35.00	35.00	35.00	17.50
Liquid Volume Flow	m3/h	2.031	2.031	2.031	2.031	1.016	1.016	1.016	0.5078
Heat Flow	kW	0.6677	265.0	0.6101	0.6677	0.3051	0.3051	0.3051	0.1525
		7	to application	8	Ghe	Lhe	10	11	LP
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	0.0000	1.0000	1.0000	1.0000
Temperature	K	300.0	300.0	300.0	299.8	300.0	299.8	299.8	300.5
Pressure	bar	13.50	13.40	13.40	1.400	13.40	1.300	1.300	1.300
Molar Flow	kgmole/h	15.74	15.74	15.74	15.74	0.0000	15.74	47.21	15.74
Mass Flow	g/s	17.50	17.50	17.50	17.50	0.0000	17.50	52.50	17.50
Liquid Volume Flow	m3/h	0.5078	0.5078	0.5078	0.5078	0.0000	0.5078	1.523	0.5078
Heat Flow	kW	0.1525	0.1525	0.1525	0.1525	0.0000	0.1525	0.4576	0.2101

Figure 4.1: Steady state simulation of Compressor station

The steady state simulation is done for compressor station as shown in fig(4.1). All the properties are attached with flow sheet. The main goal is to develop a dynamic simulation to test the control scheme for suction and discharge pressure control so later it can be implemented with PLC.

When doing simulation, the inlet or boundary stream must be well defined. In CORS system, inlet condition is
P=1.05 bar
T=300 K
Mass flow rate=70g/s
This three parameters are enough to define inlet stream. He is injected at this condition to compressor. Compression increases temperature of he so, cooler is required and then stream required for coldbox is generated and passd to application. A part of main stream is splitted with TEE and join the LP line to recycle the flow alongwith flow from buffer tank.

4.1 Dynamic Simulation of Compressor system

Dynamic simulation gives meaningful insight into process. Actually whats going on in the plant, we can see and analyse from dynamic simulation. We can test our developed control scheme through dynamic simulation with the help of stripcharts. Also we can log the values in excel sheet and then analyse and compare various parameters. The developed flowsheet is shown in fig 4.2. where,two control loops are designed.1)suction pressure control and 2)discharge pressure control. Aspen solves the dynamic case with the help of pressure-flow and material balance equations.

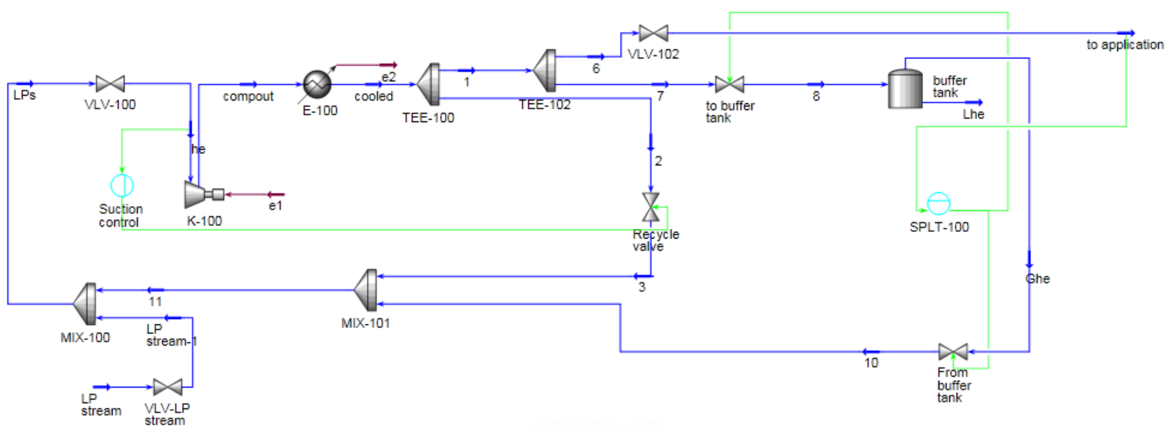
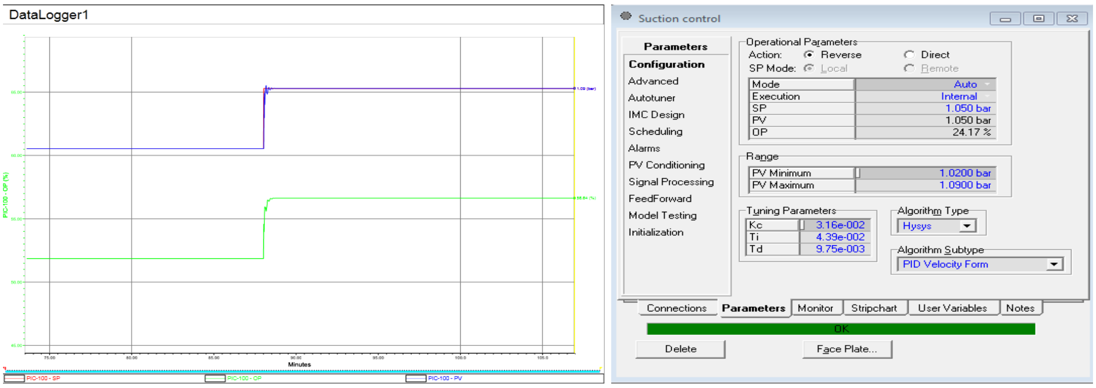


Figure 4.2: Dynamic simulation of compressor station

While doing dynamic analysis one must take care of few points. In Dynamics mode, you can specify the pressure and/or flow of a material stream in a flow sheet. To satisfy the degrees of freedom of the pressure-flow matrix, you must input a certain number of pressure-flow specifications. The volume balance equations, resistance equations, and pressure-flow relation equations make up a large number of equations in the pressure-flow matrix. However, you should be aware of the specifications that are needed before the matrix solves. In almost all cases, a flowsheet being modeled dynamically using pressure-flow requires one pressure-flow specification per flowsheet boundary stream. A flowsheet boundary is attached to only one unit operation. Examples of such streams are the models feed and product streams. All other specifications for the flowsheet are handled when each unit operation is sized using the conductance or valve flow coefficient. Aspen HYSYS also help with this through dynamic assistant. It suggests the modifications to do when moving from steady state to dynamic state[19].



(a) Step response for suction control loop (b) PID Controller parameters

Figure 4.3: Response of suction control loop with PID parameter

Fig.4.3 shows response of the suction control loop. From graph we can say that PV is maintained at desired set point. Valve is arranged in reverse action. So,when we move set point from 1.05 to 1.09 recycle valve opening is increased from 52% to 56.64%. PID controller for suction is tuned with auto tuner and the parameters are shown in fig.4.3

With suction pressure change, stream at compressor output temperature and mass flow is varied according to fig.4.4

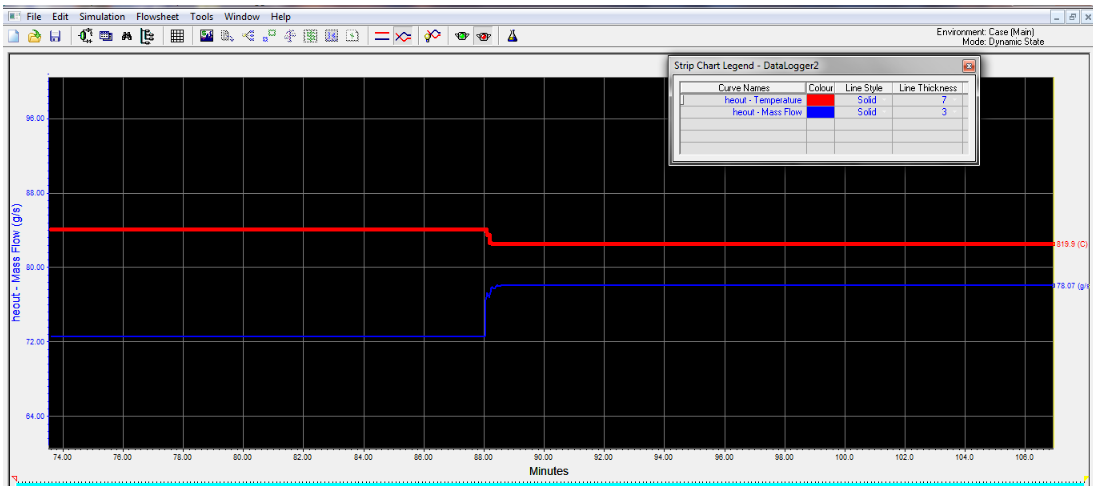


Figure 4.4: change in temprature and mass flow rate of outlet stream with change in suction pressure

4.2 Aspen HYSYS as a Model Identification Tool

Here, Aspen HYSYS is explored to develop a compressor dynamic model that can be used in actual implementation of the control scheme. With aspen we can see parameter property change with change in input. The idea is to analyse input-output data pairs and find a suitable plant model which will represent plant dynamics as a transfer function. A measured inputoutput of the plant can be represented as a first or second-order linear dynamical models in either a single-input single output (SISO) or a Multi-Input Multi-output (MIMO) form[20]. We can have number of possible IO data pairs for compressor as shown in fig.4.5.

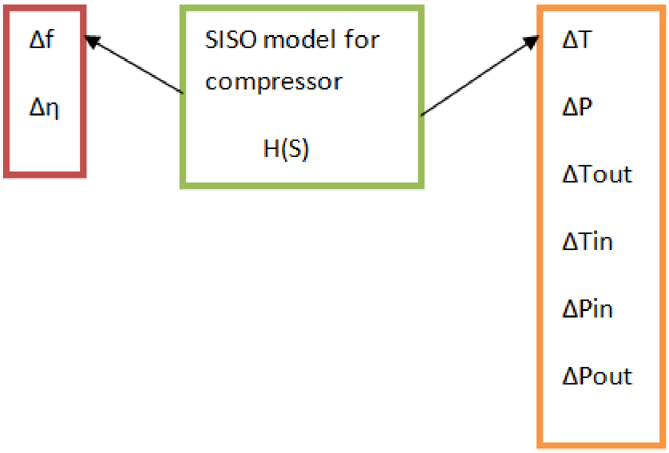


Figure 4.5: possible combination of data pairs

Finding an appropriate identification model can be itemized as follows:
(a) measure input and output data pairs of the system
(b) select an appropriate mathematical model
(c) determine model parameters of the measured system and
(d) verify and validate candidate model.

The model can be found by applying a unit step function to the input of the plant. It is the most popular one to identify an unknown dynamical linear system. After measuring input-output data pairs of the system, if a first order or second order dynamical functional relation is able to be observed, this function is called an approximation or a black-box model [21,22]. Otherwise if a functional relationship cannot be observed, there is no linear model.

To obtain transfer function for the compressor, the compressor speed (rpm) is set to 2100 at first. After observing the steady state of the deltaT, speed is changed to 2500 rpm(unit step input). With speed change, all parameters of concern are plotted. But the parameter which is dominantly affected with change in input is deltaT as shown in fig.4.6. So this data pair is used as for model identification.

Model fits to second order system. Representing it with FOPDT system which is given in general form as,

$$H(s) = \frac{Y(s)}{U(s)} = \frac{Kp}{Tps + 1} e^{-Tds}$$

We can calculate model parameters from the graph obtained as follows. Where,
Kp=system gain=change in output/change in input
Kp=2500-2100/961.91-840.96=3.3
Tp=time to reach 63.2% of final value=23s
Td= represents the past time to observe the initial response changes after applying the input=5s
So, compressor dynamics is represented as,

$$H(s) = \frac{3.3}{23s + 1} e^{-5s}$$

Now, we can implement control system with the help of model obtained for compressor and representing valve dynamics as first order system.

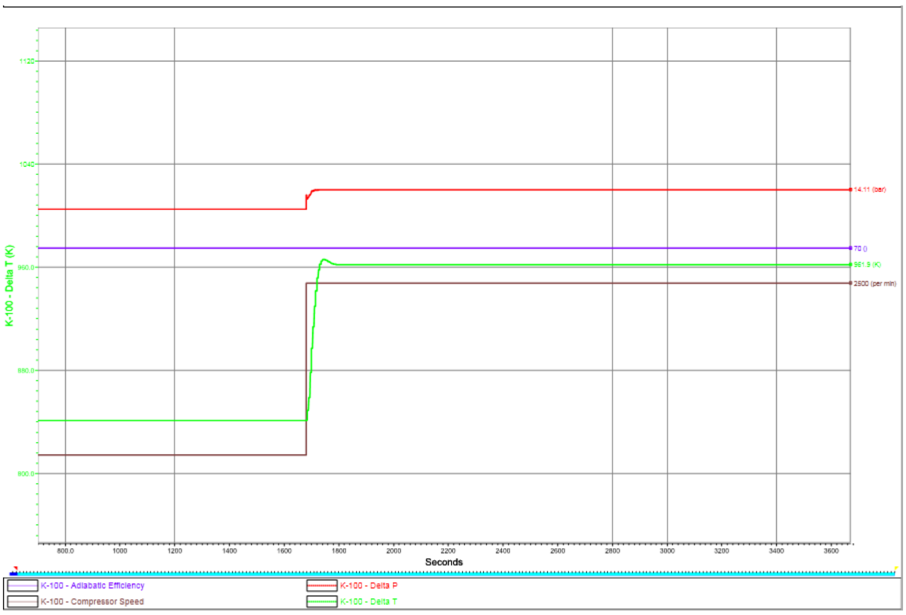


Figure 4.6: Plot of compressor Speed vs. deltaT and deltaP

Chapter 5

Implementation of Control System with PLC

5.1 Introduction to STEP 7

STEP 7 is a standard software for creating programmable logic control programs in Ladder Logic, Function Block Diagram, or Statement List for SIMATIC S7-300/400 stations by Siemens.

5.1.1 Basic Tasks

When you create an automation solution with STEP 7, there are a series of basic tasks. Fig.5.1 shows the tasks that need to be performed for most projects and assigns them to a basic procedure. Using STEP 7 software, you can create your S7 program within

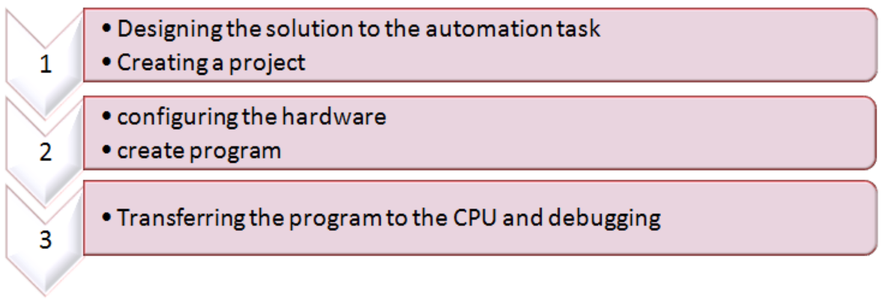


Figure 5.1: Basic Procedure for STEP 7

a project. The S7 programmable controller consists of a power supply unit, a CPU, and input and output modules (I/O modules). The programmable logic controller (PLC) monitors and controls your machine with the S7 program. The I/O modules are addressed in the S7 program via addresses[23].

5.1.2 The Simatic Manager

The SIMATIC Manager is the central window which becomes active when STEP 7 is started (fig.5.2).

5.1.3 SIMATIC Wincc Flexible

WinCC flexible is the HMI software for future-proof machine-oriented automation concepts with comfortable and highly efficient engineering. Maximum transparency is essen-

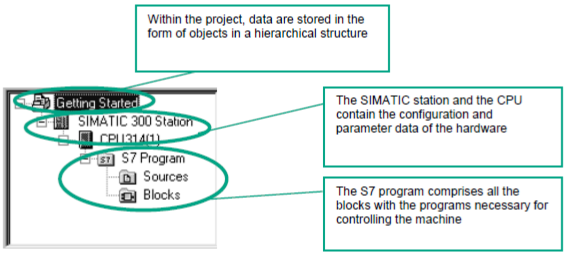


Figure 5.2: The Sematic Manager

tial for the operator who works in an environment where processes are becoming more complex, and requirements for machine and plant functionality are increasing. The Human Machine Interface (HMI) provides this transparency. The HMI system represents the interface between man (operator) and process (machine/plant). The PLC is the actual unit which controls the process. Hence, there is an interface between the operator and WinCC flexible (at the HMI device) and an interface between WinCC flexible and the PLC. An HMI system assumes the following tasks:

1)Process visualization-The process is visualized on the HMI device. The screen on the HMI device is dynamically updated. This is based on process transitions.
2)Operator control of the process-The operator can control the process by means of the GUI. For example, the operator can preset reference values for the controls or start a motor.
3)Displaying alarms-Critical process states automatically trigger an alarm, for example, when the setpoint value is exceeded.
4)Archiving process values and alarms-The HMI system can log alarms and process values. This feature allows you to log process sequences and to retrieve previous production data.
5)Process values and alarms logging-The HMI system can output alarms and process value reports. This allows you to print out production data at the end of a shift, for example.
6)Process and machine parameter management-The HMI system can store the parameters of processes and machines in recipes. For example, you can download these parameters in one pass from the HMI device to the PLC to change over the product version for production[24].

5.2 Reading Analog Input

To make closed loop control system we need to implement all the blocks and interconnect them such that it will give desired output. First task is to read current PV with sensor.

Interfacing of temperature sensor PT100 with Siemens PLC is shown here. Also, functionality is developed with wincc flexible to read value on HMI Device (PC) numerically as well as graphically and also log the values.

5.2.1 STEP 7 Project

First, we will do basic procedure, create the project in which we define CPU used, its MPI address,select programming language so that new project will be created according to our settings.Then,we will configure Hardware,in which we will define Power supply,CPU used, Analog or digital module used.

5.3 Hardware Configuration

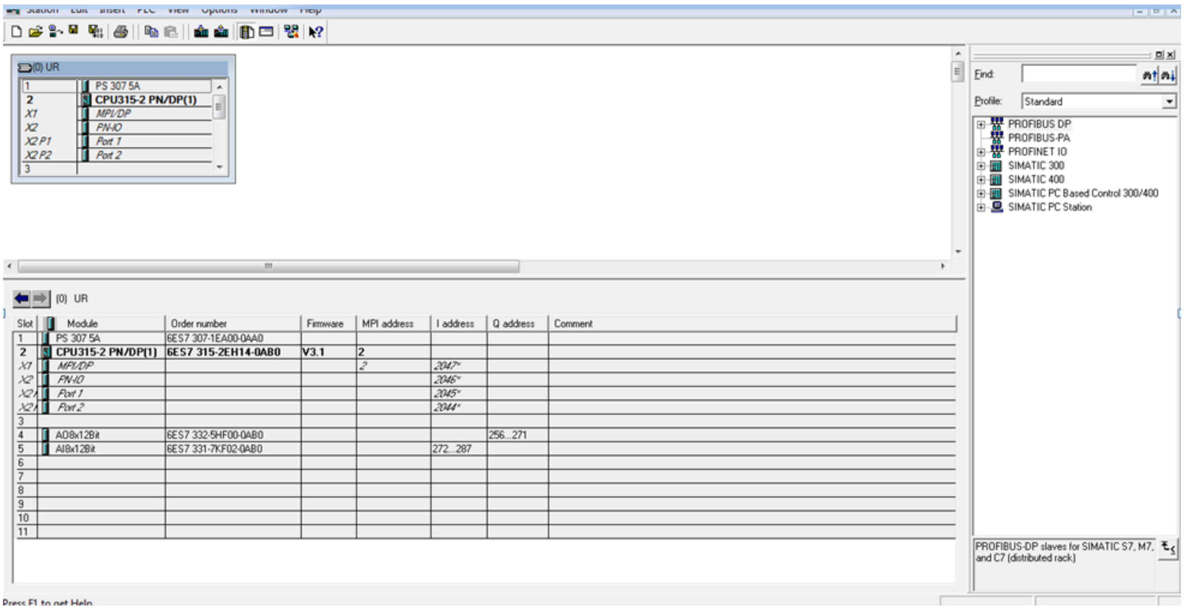


Figure 5.3: HW configuration Window

5.3.1 Power Supply Module

Name: PS 307; 5 A
ORDER NO: 6ES7307-1EA01-0AA0
Technical Specification: Output current 5 A Output voltage 24 VDC; short circuit-proof, open circuit-proof Connection to singlephase AC mains(rated input voltage 120/230 VAC, 50/60 Hz)[25].

5.3.2 CPU

Name: CPU315-2 PN/DP(1)

ORDER NO: 6ES7 315-2EH14-0AA0

5.3.3 Analog Input Module

Name:SM 331; AI 8 x 12 bit
Order No:6ES7331-7KF02-0AB0
Description
The module is Programmable for measurement type at each channel group
Voltage
Current
Resistance
Temperature

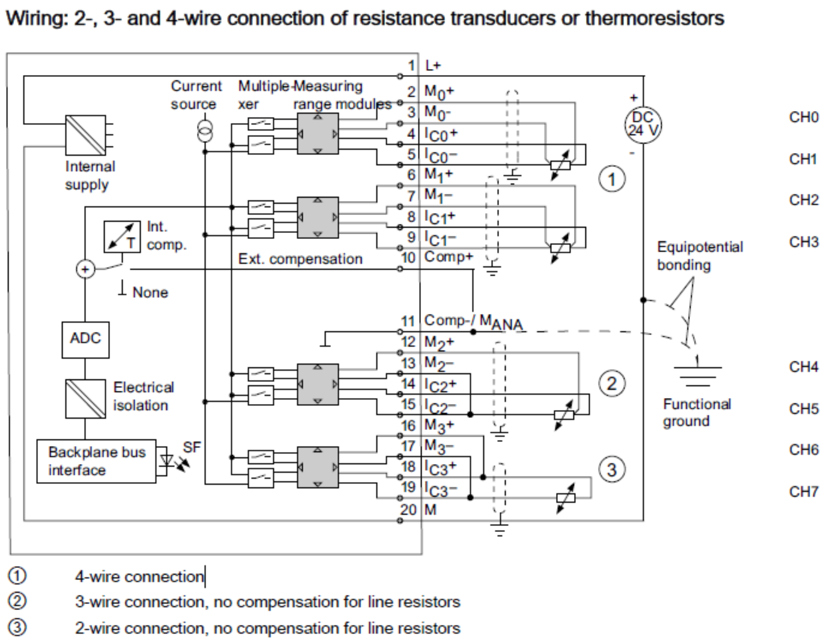


Figure 5.4: Wiring Diagram Of sensors

Measuring Range Module

The module SM331 has 4 measuring range modules (one per channel group).The measuring range modules can be set to 4 different positions (A, B, C or D) as shown in the fig.5.5(a).

Positions of the measuring range modules

The position enables you to specify the transducer to be connected to the respective channel group. Also, input this setting in analog module property window as shown in fig.5.5(b)[26].

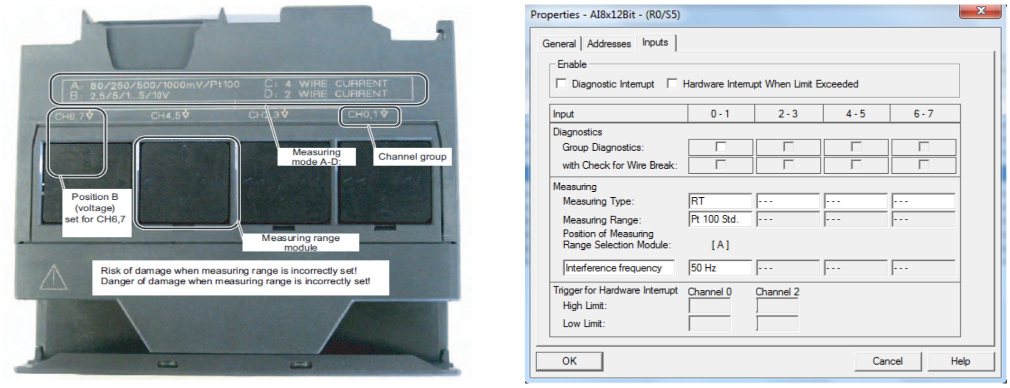
A Thermocouple / resistance measurement
B Voltage
C Current (4-wire transducer)
D Current (2-wire transducer)

5.3.4 PLC Program

First the move instruction will move temperature value which is at address PIW272 to memory word location which is of 32 bit.Then temperature will have real value,so we will convert this value to real value using convert instruction. Pt100 is designed such that it will give temperature value X 10.so we will divide the value by 10 using DIVR block.so we will have floating value of real temperature.

5.3.5 Downloading and monitoring the program

After creating the program we can download it in PLC using command download. we can individually dump hardware configuration and blocks separately so we can check for errors easily. we can put our PLC in RUN mode and test our program. If no PLC is connected then also we can test the program using S7-PLCSIM tool as shown in fig.5.7.



(a) Measuring range module (b) AI module properties

Figure 5.5: Analog input module property

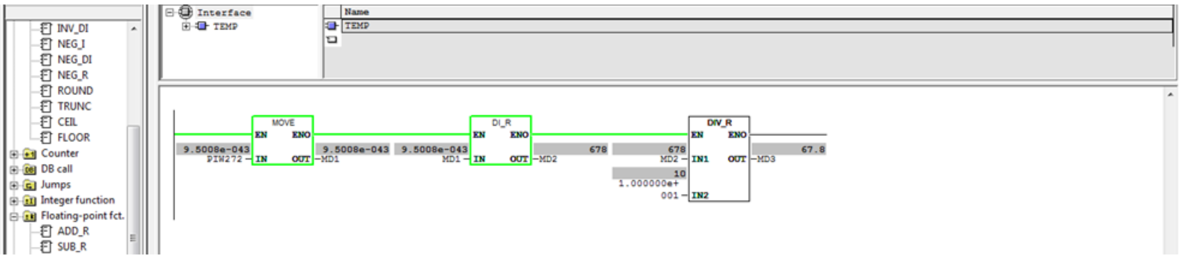


Figure 5.6: PLC Program

Fig 5.8 explains briefly how to combine software and hardware[27].

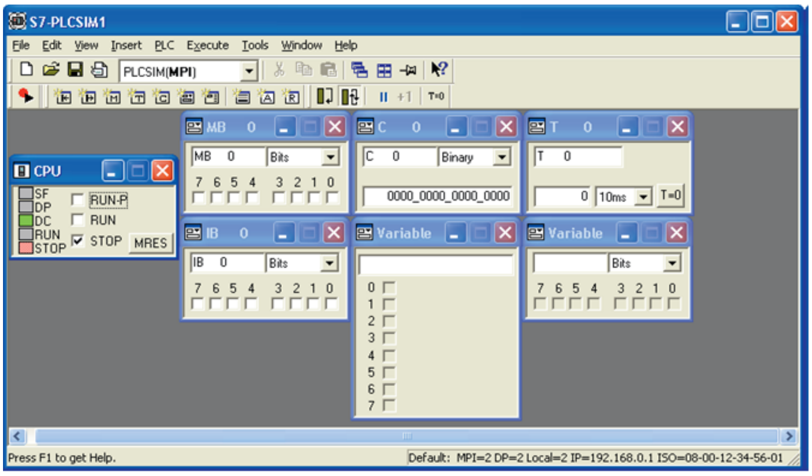


Figure 5.7: PLCSIM window

5.3.6 Display Temperature value on SCADA(Wincc Flexible)

First, we will fix up the tag where the sensor values are coming and on which address with its data type, where to log these values and alarm display to see that if limit exceeds from set point.

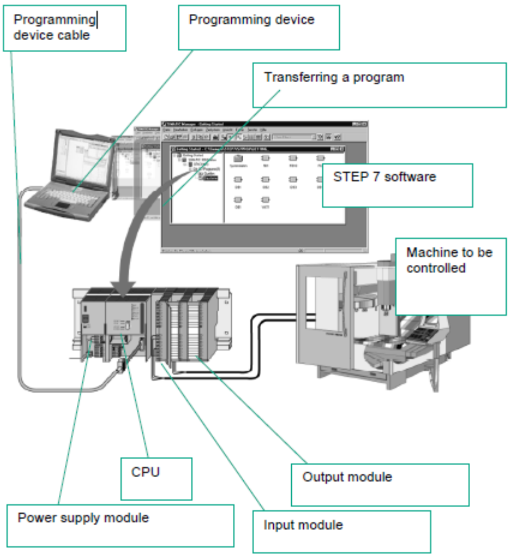


Figure 5.8: Combining Software And Hardware

Connections

PLC is connected with HMI device(PC) via Ethernet cable. so in wincc flexible from communication tab we will set the IP address of PLC CPU and PC. Make sure that the domain name should be same for both.(fig.5.9)

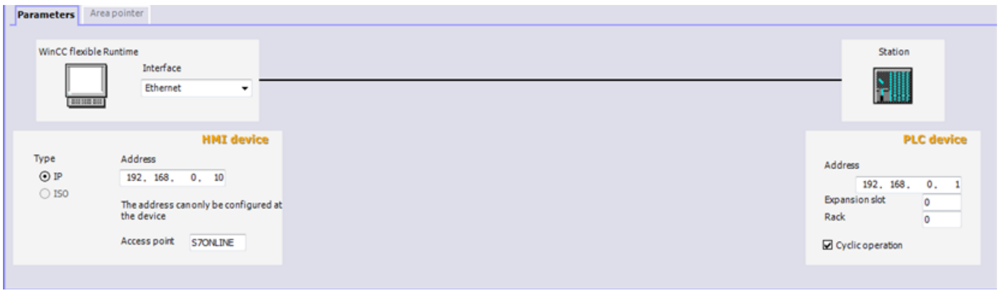


Figure 5.9: setting communication

5.3.7 Running runtime simulator

We can test the screen with runtime simulator. Here, we have connected PLC so we can directly run runtime. Here, we can see the temperature values, graph display, start and stop the logging of values using given buttons. Whole implemented system's hardware is shown in fig.5.10.

A SCADA application is also built for multiple channel interfacing with PLC and graph display of any channel of interest as shown in fig.5.11.

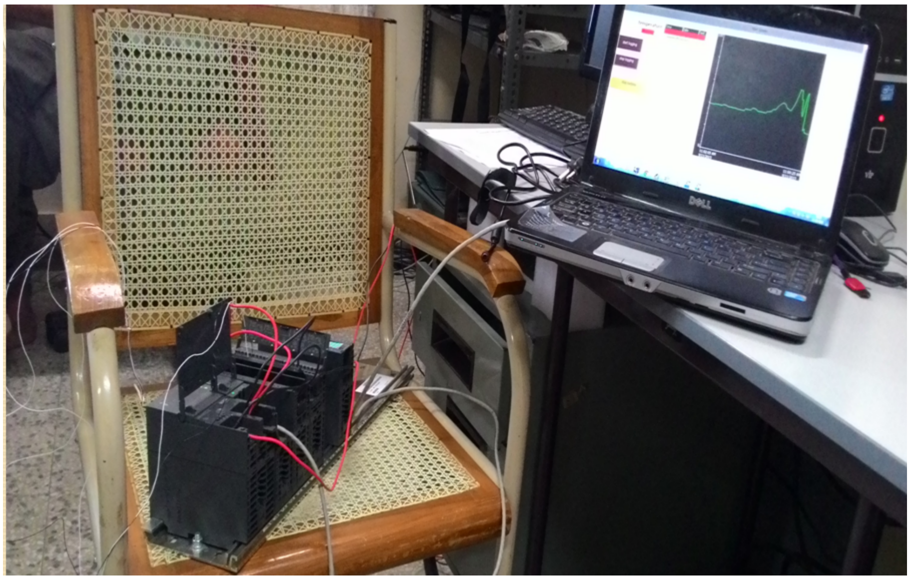


Figure 5.10: Hardware for temprature monitoring

Figure 5.11: HMI SCREEN for multichannel interfacing

5.4 Closed loop control with PID

Finding the discrete equivalent of a continuous system is desired when The controller is discrete and plant is continuous. so to simulate the whole system as discrete we must find the plants discrete equivalent[28]. As we know PLC works only on digital, first convert the continuous plant in discrete. Here it is done with numerical integration method.

Forward rectangular rule
Backward rectangular rule
Trapezoid rule (Tustins method, bi linear transformation)
Bi linear with prewarping[29].
Among this Trapezoid rule is superior as shown in fig.5.12.

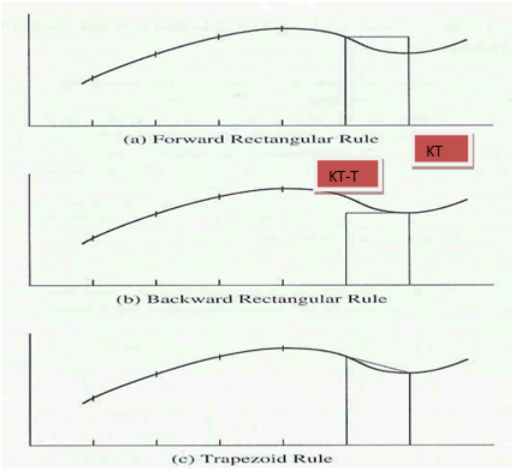


Figure 5.12: numerical integration methods comparison

Using numerical integration we can find approximate difference equation from cont.diffrential equation. And that equation can be implemented in PLC[30].

First order systems can be described with the following differential equation:

$$\dot{y} + ay = au\,.$$

The solution of this differential equation is given in the following form:

$$y(t) = \int_0^t \left[-ay(\tau) + au(\tau)\right] d\tau$$

Choosing time in discrete steps t = kT and using tustins rule we can replace laplace operator s with the discrete operator z according to the table

Method	Approximation
Forward difference	$s \to \frac{z-1}{T_s}$
Backward difference	$s \to \frac{z-1}{T_s z}$
Tustin	$s \to \frac{2}{T_s}\frac{z-1}{z+1}$

Where,Ts is the sampling time.

5.4.1 Method to obtain difference equation

A complete method to obtain a difference equation is shown here. It is done by replacing continuous laplace operator 's' with discrete operator 'z' and using time shifting property of z-transform[31].

Above equation is used to represent valve dynamics in PLC. This will make control system for suction pressure control.To make FB for valve dynamics SCL is used and called in main program. Program with its FB is shown here. In step7,To implement pid controller CONTC function block fb41,which is a continuous controller is used. It is

First order process is given as,

$$G(s) = \frac{Kp}{Tps + 1}$$

Where, Kp is process gain and Tp is process time constant.
Applying tustin's rule,

$$\frac{Y(z)}{U(z)} = H(z) = \frac{Kp}{2\frac{Tp}{Ts}\frac{z-1}{z+1} + 1}$$

$$Y(z)2\frac{Tp}{Ts}\frac{z-1}{z+1} + Y(z) = KpU(z)$$

$$Y(1+z^{-1}) = -2Y\frac{Tp}{Ts} + 2Y\frac{Tp}{Ts}z^{-1} + UKp(1+z^{-1})$$

$$Y + Yz^{-1} = -2Y\frac{Tp}{Ts} + 2Y\frac{Tp}{Ts}z^{-1} + UKp + UKpz^{-1}$$

Using z transform time shifting property,

$$Y(i) + Y(i-1) = -2Y(i)\frac{Tp}{Ts} + \frac{Tp}{Ts}2Y(i-1) + U(i)Kp + KpU(i-1)$$

$$Y(i) + 2Y(i)\frac{Tp}{Ts} = -Y(i-1) + 2\frac{Tp}{Ts}Y(i-1) + KpU(i) + KpU(i-1)$$

$$Y(i) = \frac{2Tp - Ts}{2Tp + Ts}Y(i-1) + \frac{TsKp}{2Tp + Ts}\{U(i) + U(i-1)\}$$

$$Y(i) = A\{B(Y(i-1)) + C[U(i) + U(i-1)]\}$$

Where,
$A = \frac{1}{2Tp + Ts}$, B=2Tp-Ts , C=TsKp

available in step7 system library so no need to digitize PID algorithm.(see appendix for program)

5.4.2 Output of closed loop program

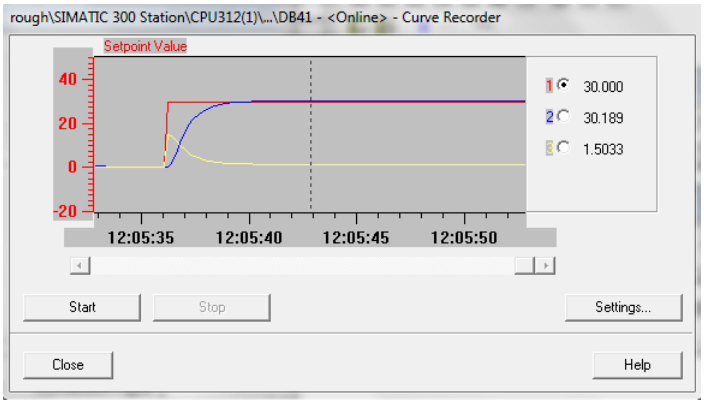


Figure 5.13: System response to unit step input

As we can see in PID assignment window's curve recorder, the response tracks the input.Yellow is the manipulated variable. Red is set point and blue is output

The PID controller parameter assignment window is shown in fig 5.14.where we can set controller parameters and also record the curves of SP,PV,MV and error[32].

5.5 Discharge Pressure Control Loop

Discharge pressure control scheme is implemented with split range control as shown in program. PV is given to PID controller and CO is splitted for charge and discharge valve, which is assumed to be linear and its characteristics is programmed in FC1 block.(see appendix) Output is seen on HMI window as shown in fig.5.15.

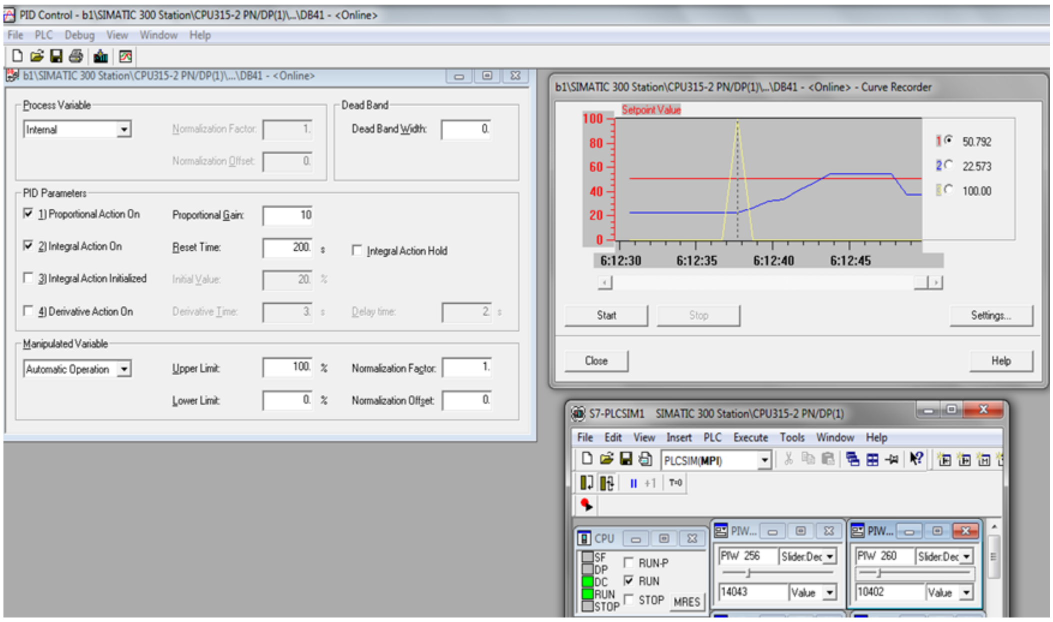


Figure 5.14: PID parameter assignment window

HMI is also developed for CORS system where we can see all necessary parameters. Also going to PID setup screen, we can change PID controller parameters and also see trend of SP,PV.(fig.5.16.) Also, whole CORS system interface is developed wherein we can monitor all parameters of interest.

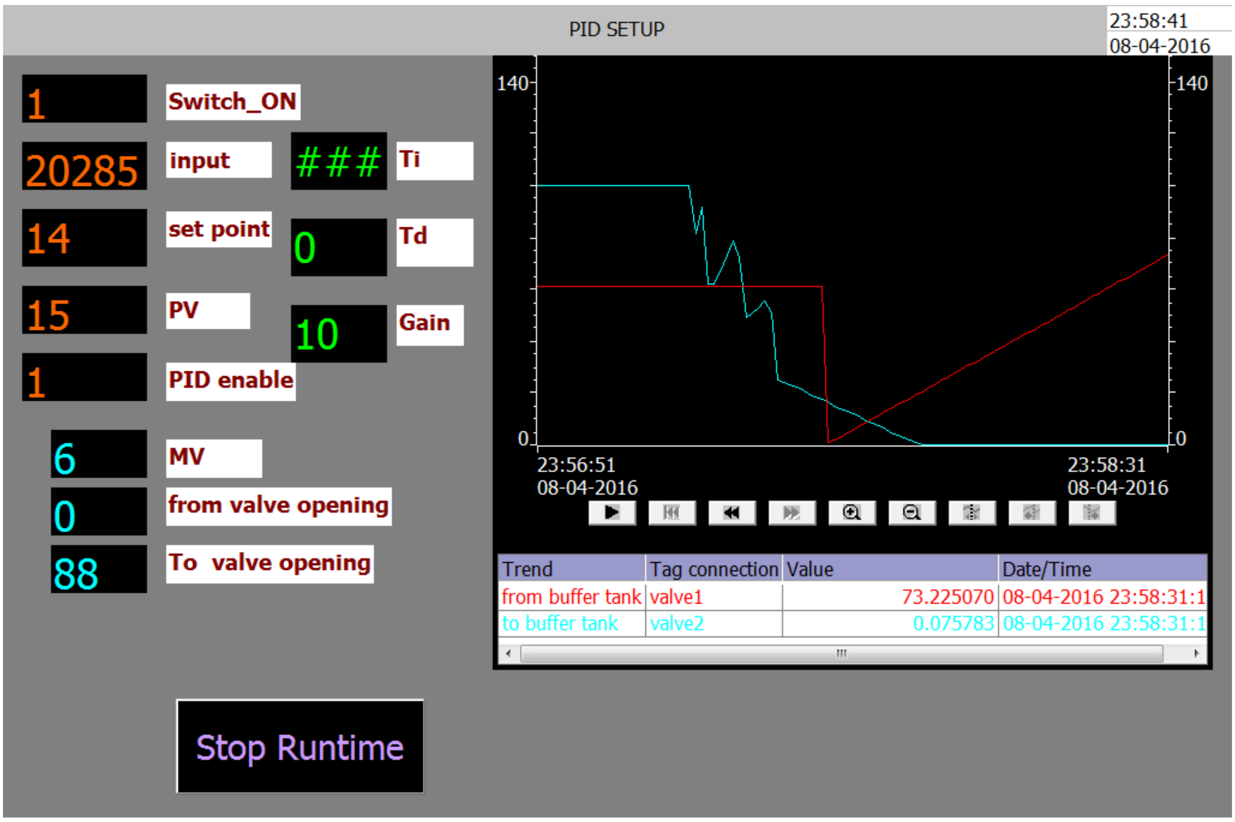


Figure 5.15: Discharge pressure control loop output

Chapter 6

Conclusion and Future Scope

Helium refrigeration/liquefier plant requires mainly CORS system and coldbox to reach upto 4.5 K. Various cycle for refrigeration is studied. The system considered is CORS. In present work, the mechanical aspects of the cryogenic plant, instrumentation involved is explored. To carry out the project work, Step 7 and wincc flexible is used. To develop a control scheme first the system is simulated with Aspen HYSYS in steady state. Then dynamic simulation is done when control scheme is designed. Response is verified with strip charts for suction and discharge pressure control loop. The main objective to use Aspen HYSYS is to develop a model for compressor that can be used to implement control loop with PLC. Control scheme used is split range control and the splitting point is decided based on valve stickiness factor mainly. SCADA is developed for CORS system with facility for data logging, value display and trend view.

Next, to design and develop a control philosophy for the same problem one can use gain scheduling also. Model identification can be done more accurately when whole cycle of plant is simulated which includes design of heat exchangers, turboexpanders, JT valve and all parts of interest. Then the developed scheme can be used to validate the result on actual hardware(test facility).

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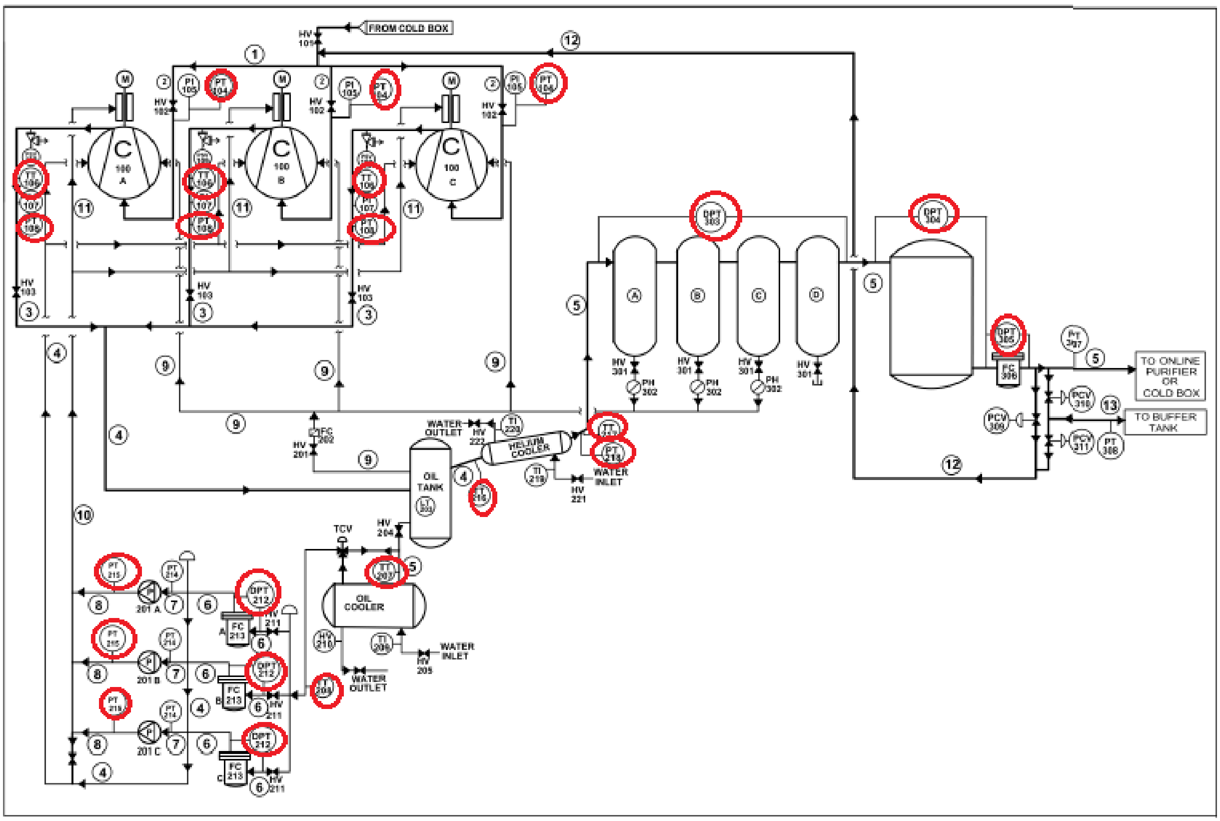
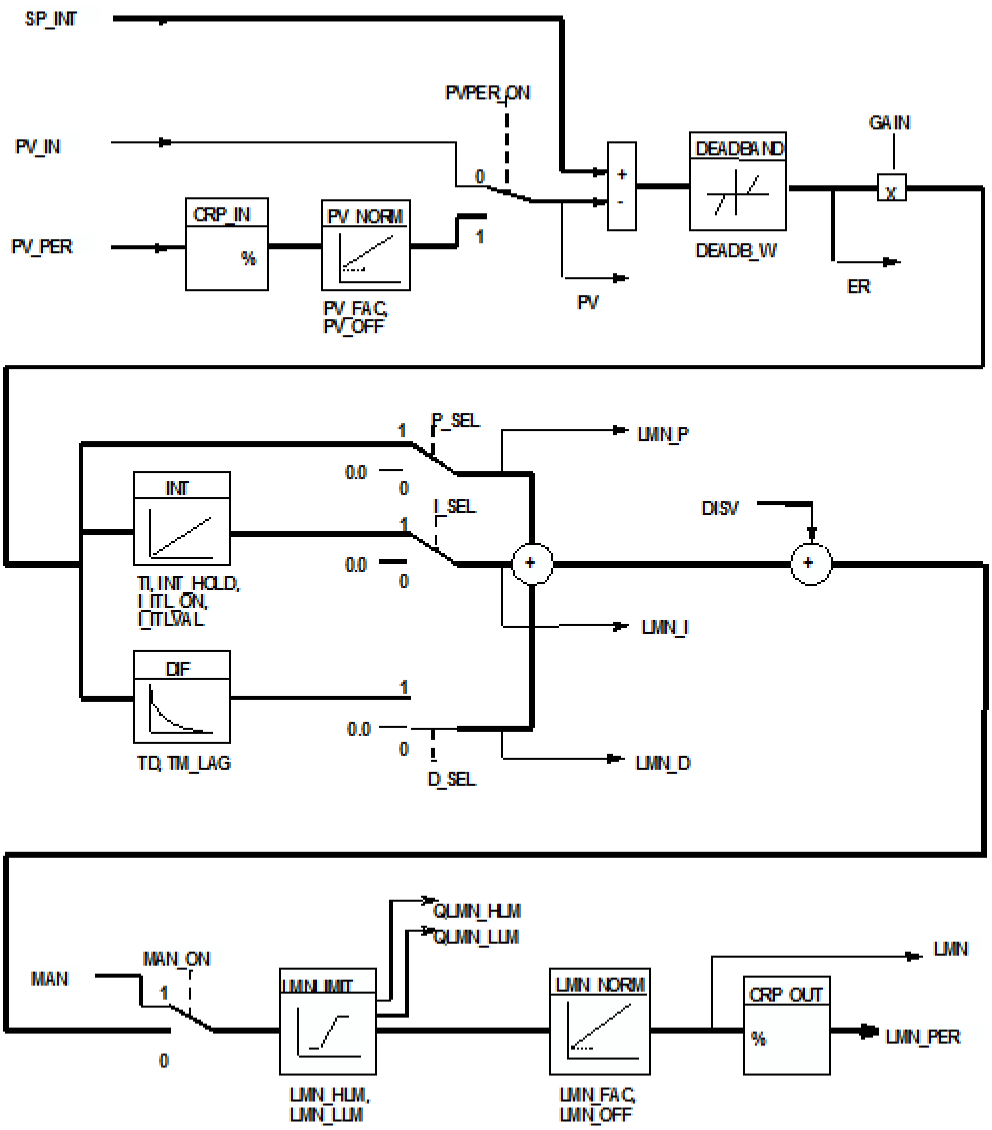
Appendix

P & IDs of CORS Plant Developed at IPR



CONT function block:Continuous controller



OB35 - <offline>

"CYC_INT5" Cyclic Interrupt 5

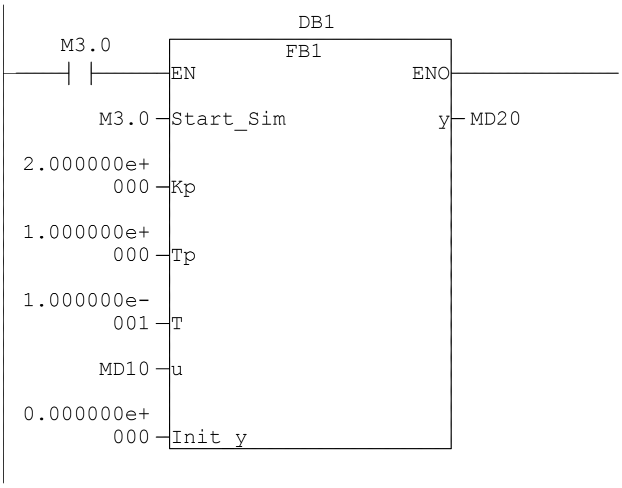
Name: **Family:**
Author: **Version:** 0.1
Block version: 2
Time stamp Code: 04/10/2016 10:35:26 PM
Interface: 02/15/1996 04:51:12 PM
Lengths (block/logic/data): 00384 00258 00026

Name	Data Type	Address	Comment
TEMP		0.0	
OB1_EV_CLASS	Byte	0.0	Bits 0-3 = 1 (Coming event), Bits 4-7 = 1 (Event class 1)
OB1_SCAN_1	Byte	1.0	1 (Cold restart scan 1 of OB 1), 3 (Scan 2-n of OB 1)
OB1_PRIORITY	Byte	2.0	Priority of OB Execution
OB1_OB_NUMBR	Byte	3.0	1 (Organization block 1, OB1)
OB1_RESERVED_1	Byte	4.0	Reserved for system
OB1_RESERVED_2	Byte	5.0	Reserved for system
OB1_PREV_CYCLE	Int	6.0	Cycle time of previous OB1 scan (milliseconds)
OB1_MIN_CYCLE	Int	8.0	Minimum cycle time of OB1 (milliseconds)
OB1_MAX_CYCLE	Int	10.0	Maximum cycle time of OB1 (milliseconds)
OB1_DATE_TIME	Date_And_Time	12.0	Date and time OB1 started

Block: OB35 "Main Program Sweep (Cycle)"

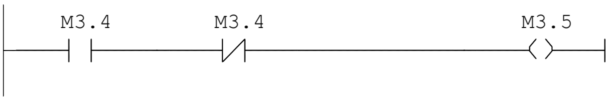
Network: 1

process block FO



Network: 2

Always OFF

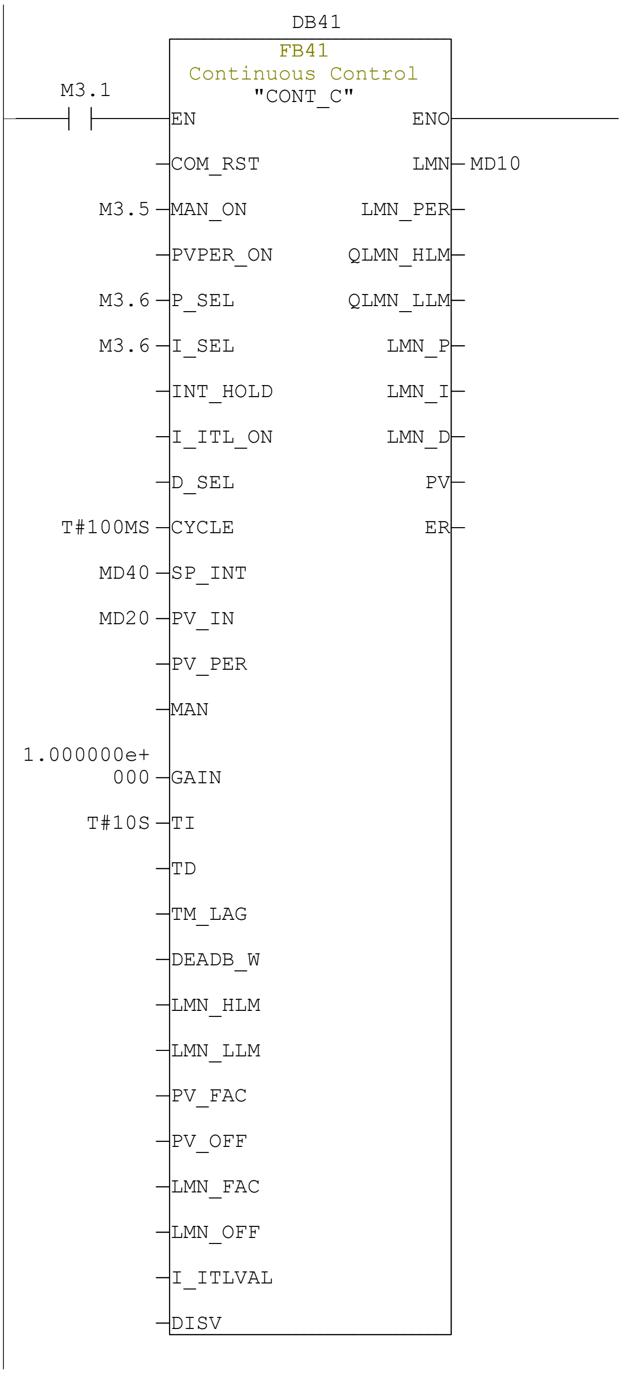


Network: 3

Always ON

Network: 4

PID control
LMN is manipulated variable.



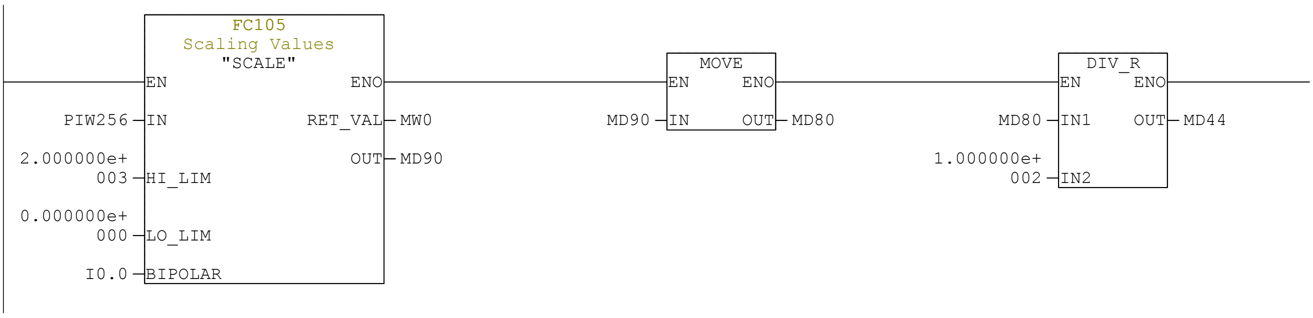
OB35 - <offline>

"CYC_INT5" Cyclic Interrupt 5
Name: **Family:**
Author: **Version:** 0.1
Block version: 2
Time stamp Code: 04/08/2016 11:49:38 PM
Interface: 02/15/1996 04:51:12 PM
Lengths (block/logic/data): 00620 00484 00040

Name	Data Type	Address	Comment
TEMP		0.0	
OB1_EV_CLASS	Byte	0.0	Bits 0-3 = 1 (Coming event), Bits 4-7 = 1 (Event class 1)
OB1_SCAN_1	Byte	1.0	1 (Cold restart scan 1 of OB 1), 3 (Scan 2-n of OB 1)
OB1_PRIORITY	Byte	2.0	Priority of OB Execution
OB1_OB_NUMBR	Byte	3.0	1 (Organization block 1, OB1)
OB1_RESERVED_1	Byte	4.0	Reserved for system
OB1_RESERVED_2	Byte	5.0	Reserved for system
OB1_PREV_CYCLE	Int	6.0	Cycle time of previous OB1 scan (milliseconds)
OB1_MIN_CYCLE	Int	8.0	Minimum cycle time of OB1 (milliseconds)
OB1_MAX_CYCLE	Int	10.0	Maximum cycle time of OB1 (milliseconds)
OB1_DATE_TIME	Date_And_Time	12.0	Date and time OB1 started

Block: OB35 "Main Program Sweep (Cycle)"

Network: 1

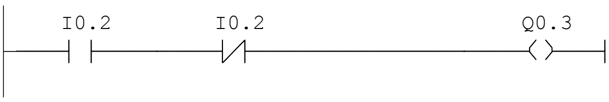


Network: 2

Always ON

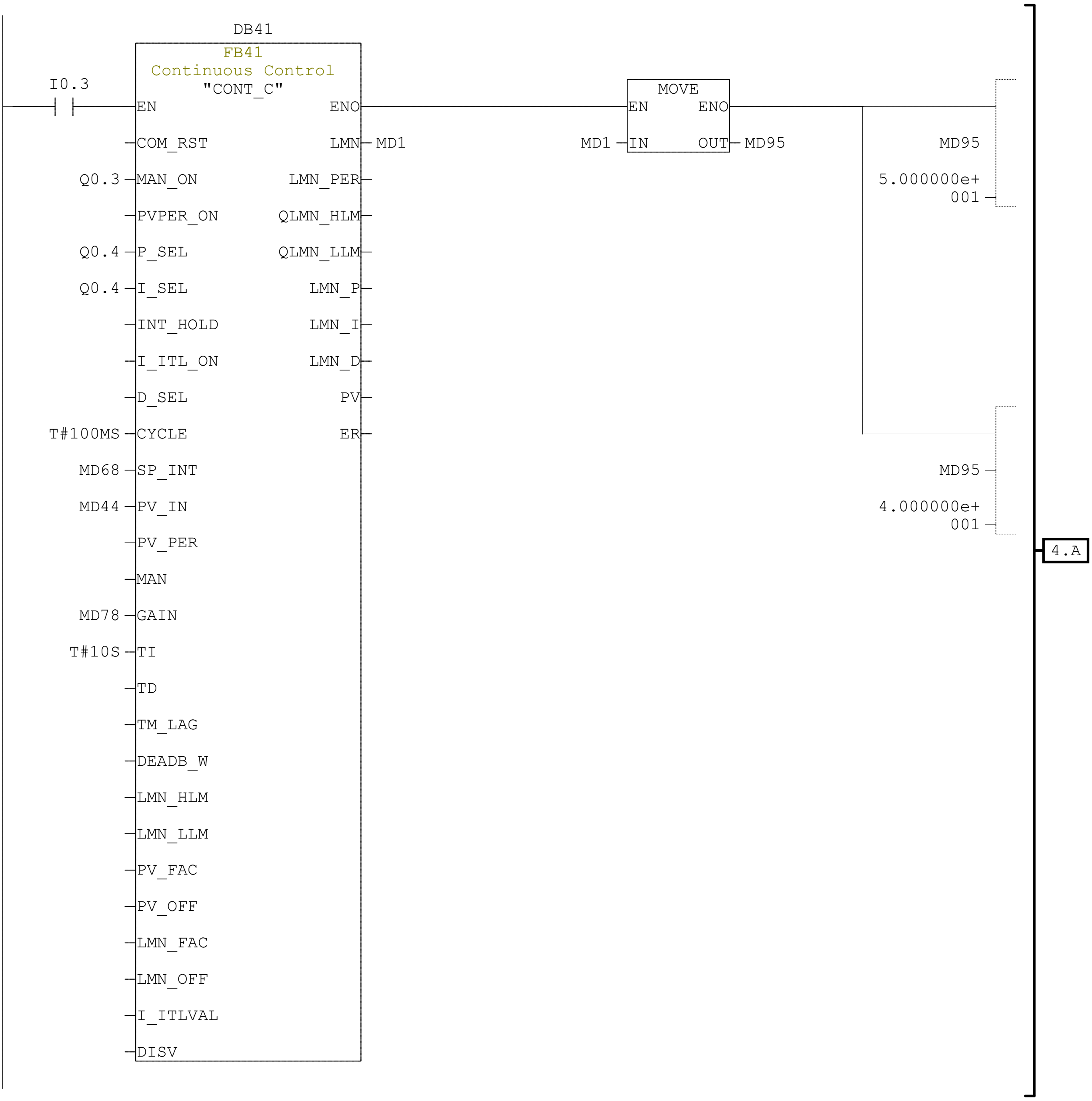
Network: 3

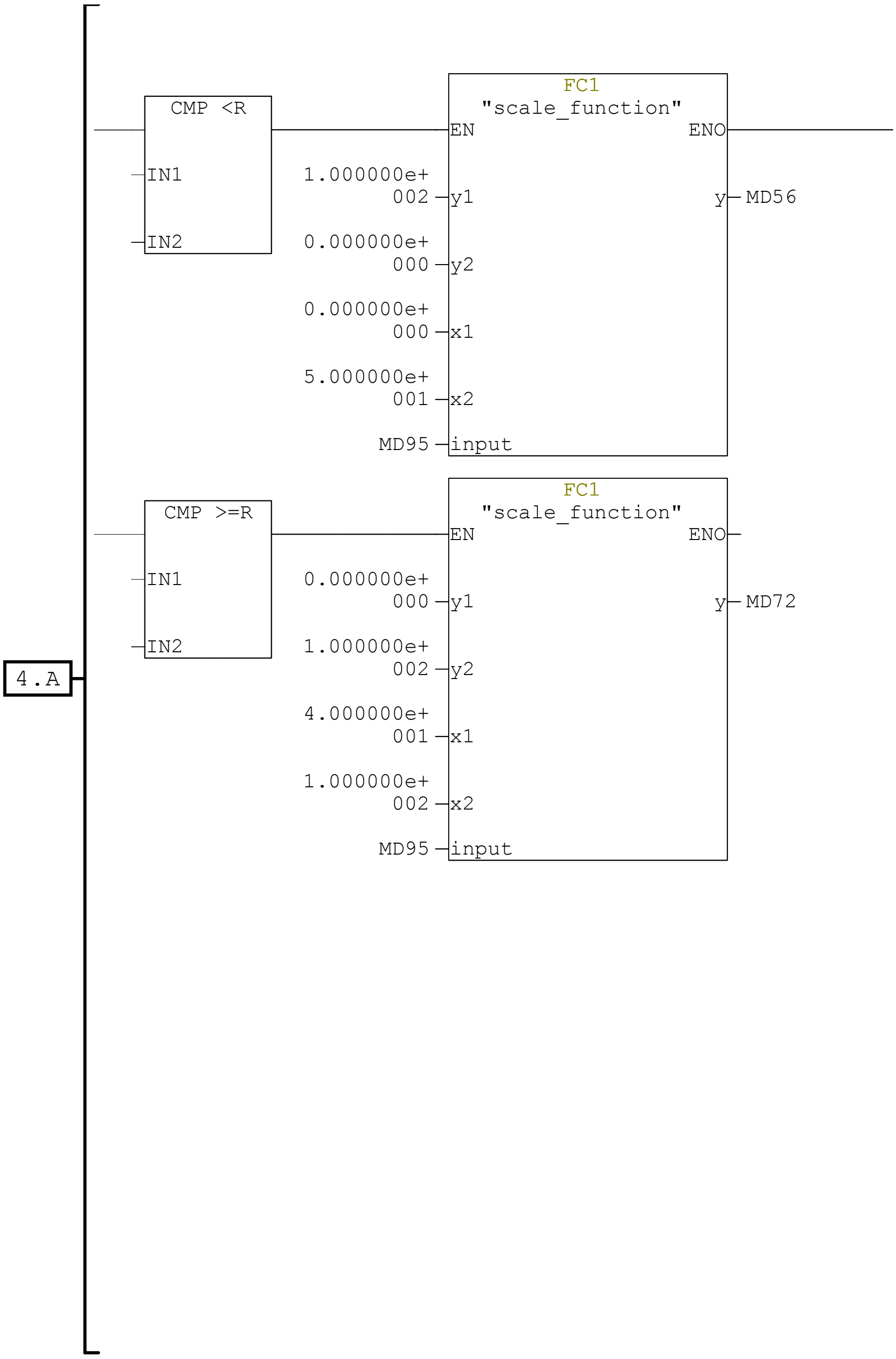
Always OFF



Network: 4

PID control
LMN is manipulated variable.




CMP <R
IN1
IN2
FC1
"scale_function"
EN
ENO
1.000000e+002
y1
y
MD56
0.000000e+000
y2
0.000000e+000
x1
5.000000e+001
x2
MD95
input
CMP >=R
IN1
IN2
FC1
"scale_function"
EN
ENO
0.000000e+000
y1
y
MD72
1.000000e+002
y2
4.000000e+001
x1
1.000000e+002
x2
MD95
input
4.A

FC1 - <offline>

"scale_function"

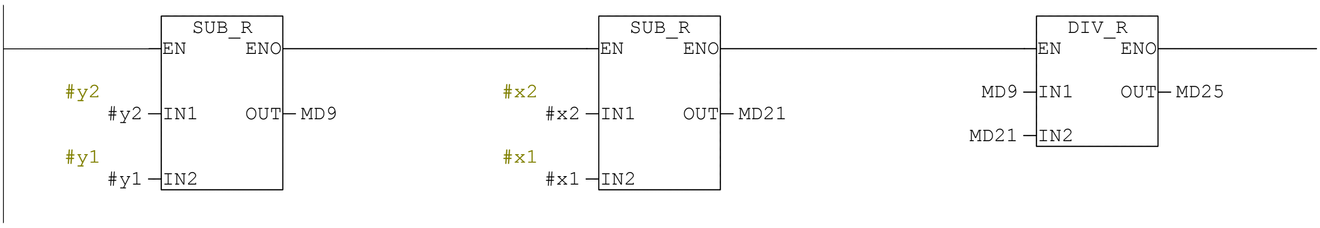
Name: **Family:**
Author: **Version:** 0.1
Block version: 2
Time stamp Code: 04/28/2016 11:12:44 AM
Interface: 04/26/2016 01:41:22 PM
Lengths (block/logic/data): 00380 00252 00000

Name	Data Type	Address	Comment
IN		0.0	
y1	Real	0.0	
y2	Real	4.0	
x1	Real	8.0	
x2	Real	12.0	
input	Real	16.0	
OUT		0.0	
y	Real	20.0	
IN_OUT		0.0	
TEMP		0.0	
RETURN		0.0	
RET_VAL		0.0	

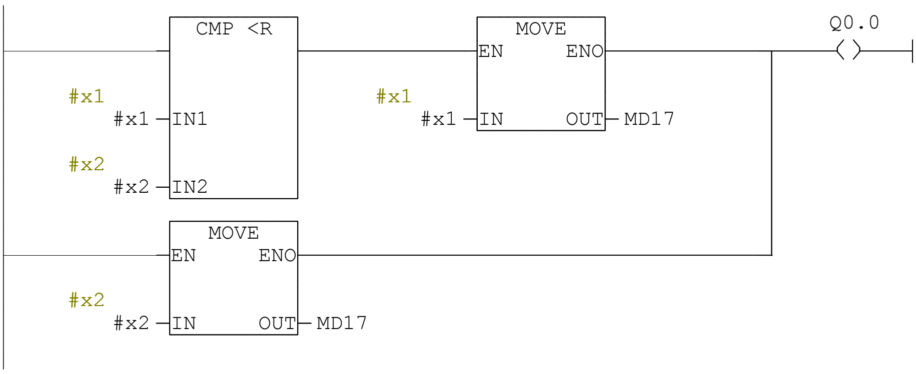
Block: FC1

Network: 1

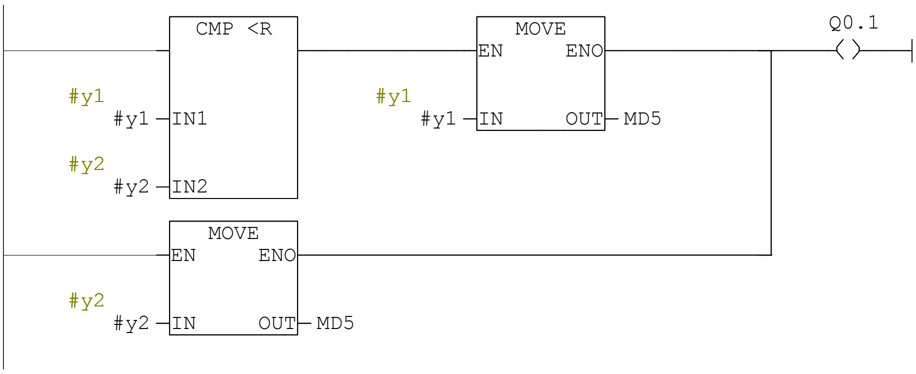
calculating m=(y2-y1)/(x2-x1)



Network: 2



Network: 3



Network: 4

calculating c=ymin-(m*xmin)

Network: 5

output scaled value=y=m*x+c