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Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Automated Central Heating System

By

Rhys Davies

Supervisor: Mr Gareth Jones
Second Marker: Dr Gary Jones

Project submitted as part of the requirements for the award
of BEng (Hons) Electrical & Electronic Engineering

April 2019

Declaration

I Rhys Davies declare that I am the sole author of this Project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits.

This work has not previously been accepted as part of any other degree submission.

Signed : Rhys Davies

Date : April 2019

Form of Consent

I Rhys Davies hereby consent that my Project, submitted in candidature for the BEng Electrical & Electronic Engineering degree, if successful, may be made available for inter-library loan or photocopying (subject to the law of copyright), and that the title and abstract may be made available to outside organisations.

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Date : April 2019

Abstract

The purpose of the following project is to research, design and implement an automatic central heating system. This will operate so that the system is controlled by a PLC so that once the temperature of an enclosed area gets to low the temperate will be controlled at its given set point by a control valve which is operated using 3 term control.

The full content of this report includes.

- Research into current and similar systems that are out there on the market.
- Research into all the hardware needed such as temperature sensors and control valves.
- A PLC program design.
- HMI Screens design.
- A fully working prototype and build cost.
- Analysis on the working prototype gathering data.
- Evaluation of the project.
- Conclusion.
- Personal Reflection.

The software packages I'll be using throughout the project are listed below.

- TIA 13.
- Microsoft Word.

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Chapter 1 - Introduction

The project that has been chosen is an automated central heating system. The concept of the project is to design a system which will keep an enclosed area at a chosen temperature by passing hot water through copper coils in a controlled amount via a control valve which is operated by a PLC.

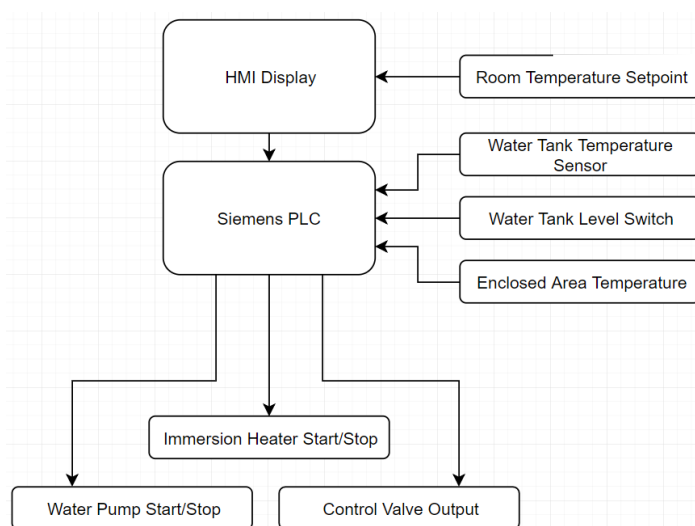


Figure 1 - Block Diagram of the System Operation

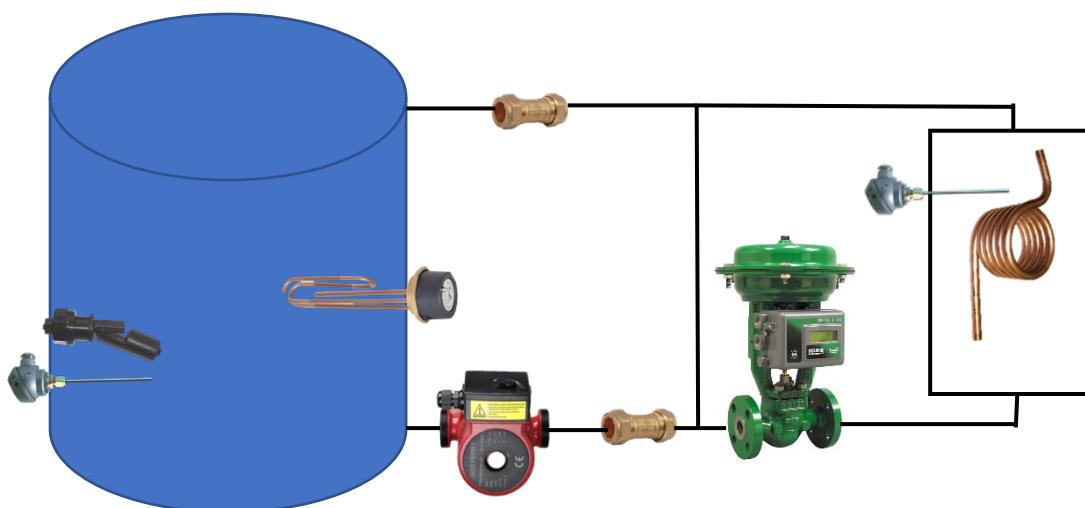


Figure 2 - Picture Diagram of the System Operation

Figure 1 shows the basic operation of the project displaying the 2 analogue inputs, 1 digital input, 2 digital outputs and 1 analogue output. The enclosed area temperature is what would be controlling the analogue output signal to the control valve. There are a number of key elements that need to be researched for the project to be a success which are.

- Selection of hardware such as temperature sensors, level switches, pumps, control valves and immersion heaters etc.
- The amount of heat transfer depending on the amount of copper coils.
- Correct type of vessel to use.
- PLC operation.

For the project to be a success the above factors need to be achieved.

Chapter 2 – Planning

2.1 – Objectives

To produce a quality report the following objectives must be achieved in order to make the requirements.

Planning	A plan such as a Gantt chart is a good way to follow a timescale and is a guideline to meet timescales. By following a gantt chart it can be seen if the project is meeting the deadlines and if so the project is running smoothly.
Research	By producing a research methodology it finds the best method to research information. Research on all the hardware is going to be time consuming but is needed due to the importance it has.
Implementation	Create a PLC programme using TIA 13 so that once complete can be sent to the fully operational prototype that will also be needed to be built. Once the PLC programme has been sent, testing can then take place.
Analysis	Analysing the data gathered from the testing of the system and to write a report explaining the results.
Evaluation	Evaluating the overall project from the very beginning all the way to the test results, highlighting areas of improvement for future project builds.

Table 1 - Project Objectives

2.2 – Project Milestones

Table 2 shows a rough estimate of the timescale for the project to be a success. This helps to keep the project running smoothly making sure each timescale has been met. This prevents a lot of work load being left to be completed close to the submission date.

Task:	End Date:
Project Start Date	8 th November 2018
Project Plan	15 th November 2018
Research	22 nd November 2018

Implementation	7 th February 2019
Analysis	11 th April 2019
Evaluation	23 rd April
Viva 1	29 th October 2018
Viva 2	24 th January 2019
Final Viva	7 th May 2019

Table 2 - Project Milestones

2.3 – Project Breakdown

The following tables shown below are the breakdown of the proposed project plan.

Project plan breakdown	Description	Start Date	Due Date
Project Proposal	To think of a project narrowed down from the 3 possible ideas.	8.11.2018	15.11.2018
Produce Gantt Chart	Produce a timeline of which each task has to be completed by.	8.11.2018	12.11.2018
Technical Specification	Produce block diagrams, flow charts and	12.02.19	14.02.2018

Table 3 - Project Plan Breakdown

Investigation breakdown	Description	Start Date	Due Date
Current Availability	Research into the current market to see if my proposed project is available.	22.11.2018	26.11.2018
Market Research	To research what advantages the project will have over existing systems.	4.12.2018	8.01.2018
Research	To research into all the hardware and software needed for the project to work.	9.01.2019	29.01.2018
Cost Analysis	Produce a cost analysis document so that the total cost of the project can easily be worked out.	30.01.2019	6.02.2019

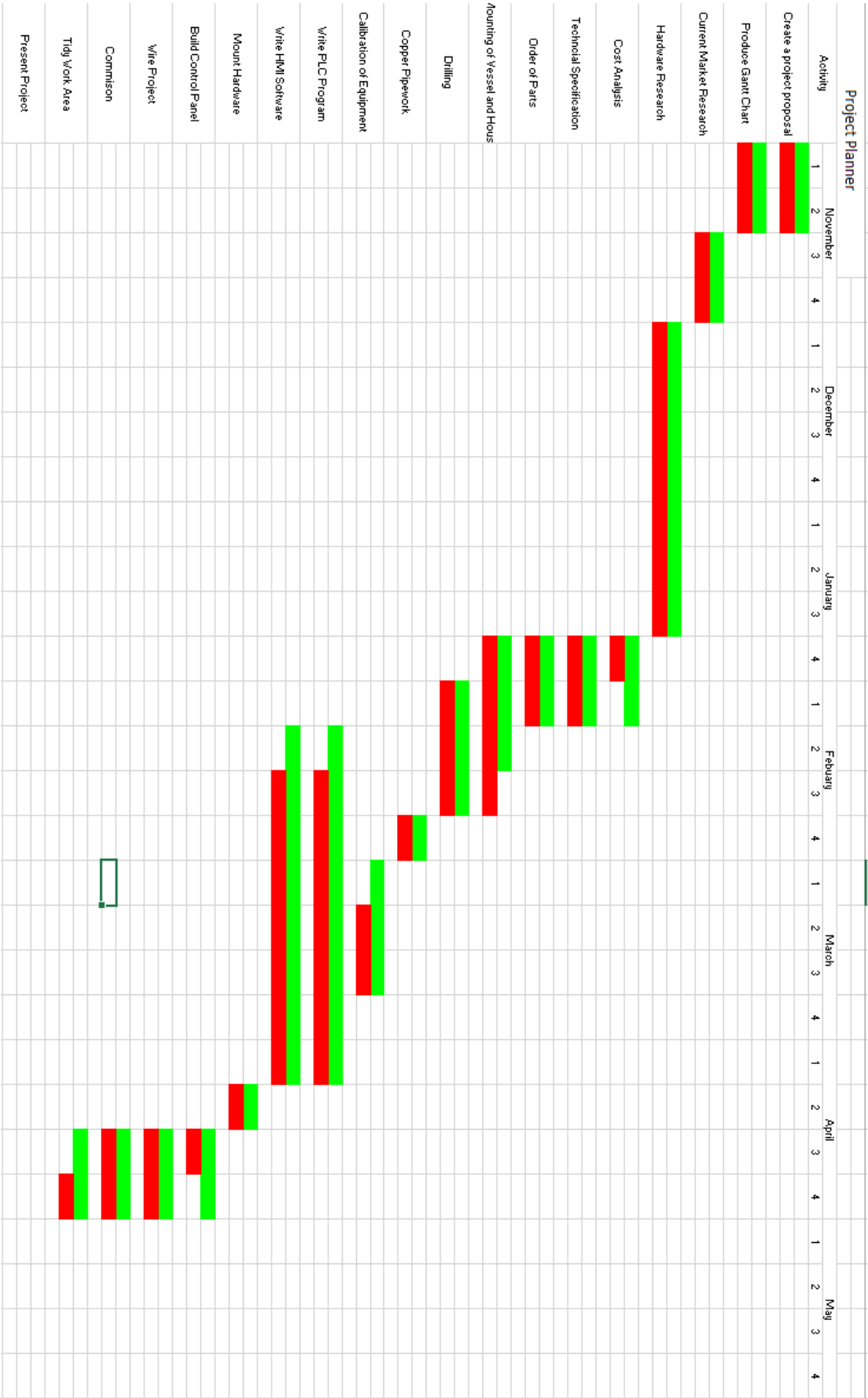
Table 4 - Project Investigation Breakdown

Implementation Breakdown	Description	Start Date	Due Date
Design HMI display screens.	Design the layout of each HMI screen for the project using TIA13 software.	7.02.2019	8.04.2019
Write ladder logic for the PLC program.	Design the ladder logic needed for the project to operate safely and efficiently.	7.02.2019	8.04.2019

Produce a fully working model of the project	Build a real life working model of the chosen project using all the hardware equipment.	1.04.2019	20.04.2019
Test Project	Power the PLC and begin testing.	22.04.2019	26.04.2019

Table 5 - Project Implementation Breakdown

2.4 – Gantt Chart



Chapter 3 – Research Methodology

3.1 – Research Onion

Methods used to source information that help to achieve an understanding of what needs to be completed possibly within a certain time scale. A research onion helps to view the research methodologies because it breaks down each method and describes each layer, the theory is that if each layer keeps on getting peeled off eventually the core would be reached resulting in exposing of the research methods.

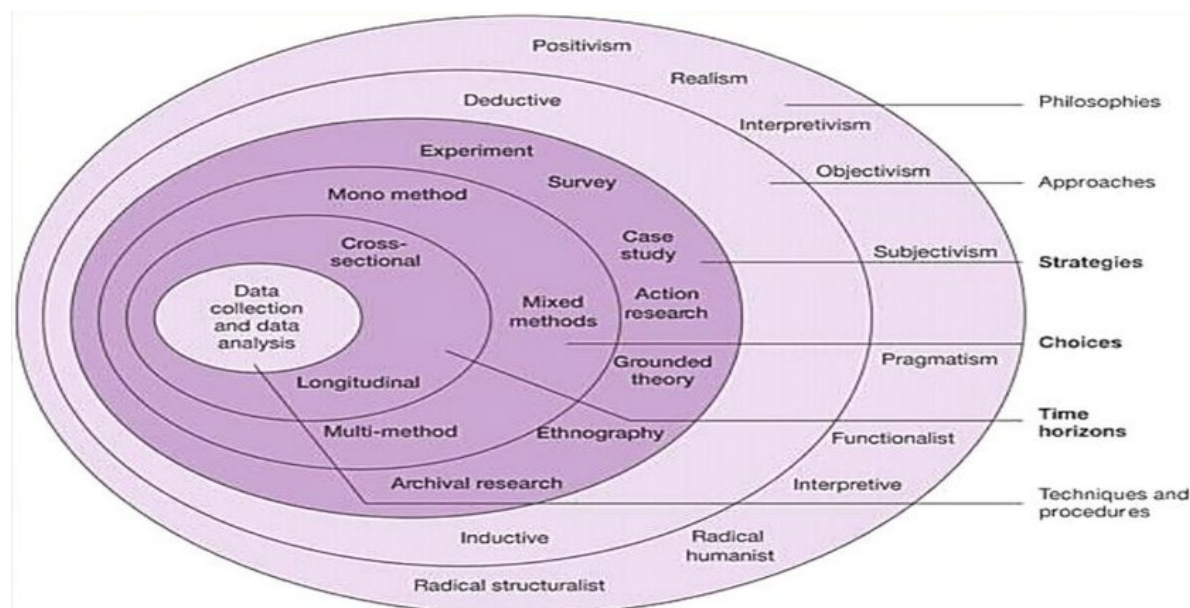


Table 6 - Research Onion

3.2 – Research Philosophies

Research philosophies is the first layer of the research onion. The idea of the first layer of the onion is to make the researcher think of what type of research is needed. A few of the philosophical instances are described below.

- **Objectivism** – Makes the researcher “aware of a social phenomenon.” [1]. For example when an employee is aware that a big boss is going to be passing his or her work area to inspect the work that has been completed the employee will try and do a better job on that certain day dissimilar if the employee was not aware that the boss would be coming.
- **Positivism** – Creates research questions through data collection and “hypotheses that you can test.” [1]. “Positivism is based on the idea that science is the only way to learn about the truth.” [2] All the research should aim to explain and predict and that positivism abides by the rule that only factual knowledge is gained from personal observation, ideally using all your senses such as touch, sight, smell, taste and hearing.
- **Realism** - It in its processes and belief that social reality and the researcher are independent from one another, it is similar to positivism and so will not produce biased results.

So they also are different in some ways because even though realism thinks that scientific methods are not great
It believes that all the theory can be revised and that without entire contents our ability to know for sure what reality is can not exist. [3]

3.3 – Research Approaches

The relevance of hypotheses to the study is the main distinctive point between deductive and inductive approaches. Deductive approach tests the effectiveness in hand, whereas inductive approach contributes to the development of new theories and conclusions. Abductive research starts with research questions and objectives that need to be completed during the operation of the research.

- **Deductive Research Approach** – A deductive approach is preoccupied with designing an existing theory based hypothesis and then creating a research strategy to measure hypothesis. This was stated that deductive means reasoning from the specific to the general. If a correlation or link seems to be indicated by a particular belief or case example, it may be true to some belief. [4]
- **Abductive Research Approach** – The research process begins with ‘surprising facts’ or puzzles in abductive approach and their reasoning is devoted to the research process. When a researcher encounters an empirical occurrence that cannot be explained by the range of theories, ‘surprising facts’ or ‘puzzles’ could arise.

3.4 – Research Strategy

As a primary methodology strategy used in this project is the document assessment technique. Research on the theory and installation of the new equipment to be installed together with a firm understanding of the theory behind the plant to be controlled was required. Since this project offers simple proof of principle, a clear understanding of the theory behind all of the technology that would be used to implement the project in the modern world was feasible. All this was acquired from documents published and adhered to the project.

3.5 – Time Horizon

This project primarily adopted a cross sectional horizon as information gathered from the system will at some point be a glimpse of the overall performance. Considering that the data collection would be of the temperature sensor performance under multiple variables such as water glow and the amount of heat transferred. This is the ideal technique to use. Needless to say, the most reliable results can not be required due to the complexity of this technique, as it does not enable data collection over an extended length of time and the results will be solely based on the test conditions set at the time. Furthermore, this is the appropriate measure since the study is not supposed to evaluate a change over a indefinite period of time.

3.6 – Data Collection

This report is the statistical analysis consisting of both of these primary and secondary data. Secondary data defines the vast majority of the research for the early stages of the research, as it would be necessary to achieve an real understanding of the hypothesis and principles behind the technology to be used. The research still includes primary data as has already been conducted by published studies which provide valuable judgement into how the hypothesis relates to a real scenario.

Chapter 4 – Investigation / Market Research

Research into the market competition needs to be carry out to help identify what is currently out there operating. By performing market research it possibly creates new ideas

that could be added or even modified to maximise its market value. Also by researching the current market it helps to create a unique project by giving the builder an idea of what could be useful to have or not. The project needs to be attractive to people to purchase so a cheaper product would stand out over similar products. Advantages / disadvantages and benefits of the project are listed in this chapter as well as the demand for a central heating system.

By performing research on central heating systems, the following products caught interest.

There are two main ways that homes can get heated:

- Where the heat is produced centrally and then distributed around to each room normally using radiators.
- Heat is produced individually by heaters or fires in each room. [5]

4.1 – Wet Central Heating Systems

With wet central heating systems, a central heat source such as a boiler produces hot water which is then distributed around the home via heating radiators and becoming available for hot taps and showers.

Generally this is considered the most cost effective and efficient form to provide heat and hot water for a property and is the most common form of heating in UK homes today with over 93% having a central heating system. [6]

4.1.1 – Boilers

In most wet systems, the boiler heats the water that feeds the system. [5] The boiler will use either gas as a fuel or either oil or LPG (Liquid Petroleum Gas). Oil and LPG are used in homes where mains gas is unavailable.

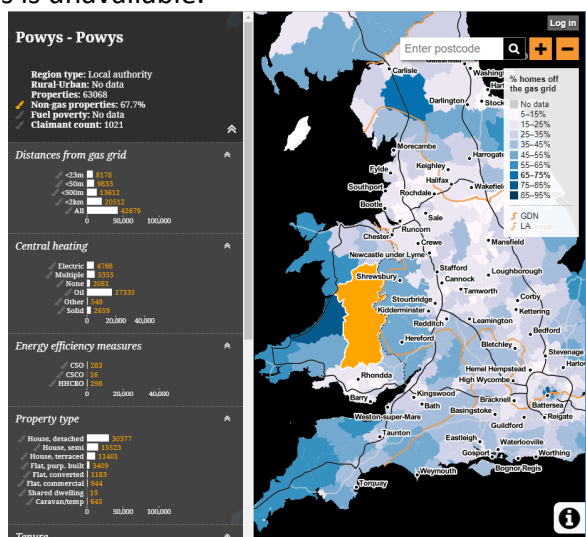


Figure 3 - Gas map of the UK

Figure 3 is a gas map of most of the UK clearly identifying which areas have a high or low percentage of homes that are off the gas grid, meaning a percentage of homes that use gas to heat and cook food in their homes.

There are three main types of boilers:

- Heat only (Regular)
- Combination (Combi)
- System

4.1.2 – Heat Only Boiler

Heat only boilers can heat a home very efficiently. The heat only boiler uses a storage tank with two feeds one for hot water and the other for cold water. The water is pumped through the system to which will then get heated up and stored as hot water it is then only used when needed for hot taps for example. Hot water is pumped around the home to keep it warm all depending if the thermostat controller is asking for the rooms to be heated. Heat only boilers are known as regular boilers because it is the conventional way of heating a home. If the space for a cold and hot water feed then a system boiler is recommended which adequately does the same job as a regular boiler but circle the tank all in one rather than a separate unit creating more space. Heat only boilers are preferred for larger homes or businesses [7]. This is because they don't rely on head pressure and supplies constant hot water throughout the building.

Positives of Heat Only Boilers

- Heat only boilers still operate perfectly when the main supply pressure is low.
- Due to the heat only boiler being very simple and not having many components maintenance is cheap and easy.
- Heat only boilers can provide multiple buildings with hot water at the same time.

Negatives of Heat Only Boilers

- Two separate hot and cold water storage tanks are needed to feed the central heating system so a large space is needed.
- The showers and taps would have low pressure and flow.
- They don't deliver hot water on demand, meaning that a wait for the water to heat up again once the storage tank runs out of hot water. If a bath has been filled for example there may not be any hot water for a while subsequently [8].
- Less efficient than a combi boiler due to the heat lose overtime from the hot water cylinder. [8]

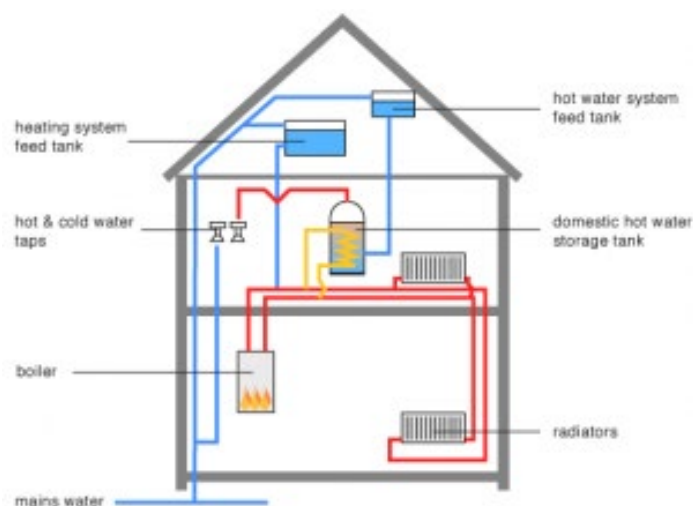


Figure 4 - Heat Only Layout Diagram

4.1.3 – Combination Boiler

A combi boiler is a space saving idea which is increasingly popular choice within the homes of the UK. “Combi’s are now in for well over half of all the new domestic boilers installed in Britain every year” [9]. Combination boilers combine the operation of a central heating boiler and an immediate water heater. A combi boiler removes the need for separate water tanks due to the cold water supply is directly plumbed in from the mains water and then to get hot water the boiler instantly heats up the cold water. The combi unit contains a small hot water storage tank that holds a small amount of water that is kept hot all the time [10]. The operation of a combi boiler consists of a fuel supply which is either gas or oil is directed to the burners in the boiler. For the burners to come on the hot water tap must be turned on which asks for hot water to clean dirty dishes for example. When using the hot water, the water runs over a paddle switch which turns the burners on within the boiler which heats the water for the taps. Both the central heating pipes and the utilities pipework all pass through the same heat exchanger so both systems are hot at the same time. This doesn’t mean that if a hot water tap is open filling the bath that all the radiators are going to be on, just the pipework selected.

Positives of Combination Boilers

- Further benefits of a combi boiler includes hot water being delivered through your taps or shower at mains pressure. So you can enjoy powerful showering without the need for a pump. [9]
- There is a limitless supply of hot water due to it being heated regularly. There is no cylinder of hot water so no extra installation costs as well as heat loss costs. [10]
- A combi boiler can be installed into tight spaces.
- A lot less carbon emissions emitted to the atmosphere.

Negatives of Combination Boilers

- Only disadvantage with combi boilers is that they are expensive to purchase and install.

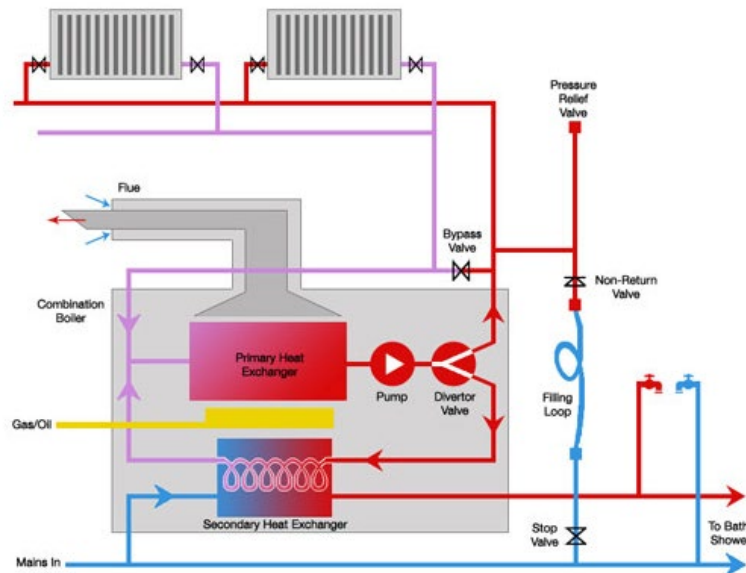


Figure 5 - How a Combi Boiler Works

4.1.4 – System Boiler

There is an increasing trend to combine different parts of the central heating system within the same casing as the boiler. These products are known as system boilers. They usually contain the boiler, safety devices, controls, pumps and designed for the sealed systems they may also contain an expansion chamber and low pressure cut of sensors. Sealed systems usually operate at pressure of about one bar when cold which rises due to water expansion to between 2 and 2.5 bar when the system is hot [10].

Positives of System Boilers

- All major components are built in resulting in less space being used. The only external part is a tank that stores the hot water.
- System boilers are good for high hot water demand loops such as households with more than 1 bathroom, due to it using a large tank meaning that multiple taps can be used at the same time.
- System boilers don't need an expansion vessel or a cold water tank. This gives the ability of having a system boiler even if the house doesn't have a loft.
- With the water supply being delivered from the mains instead from a tank in the loft gravity feeding the pipes stronger water pressure from the taps can be achieved compared to standard boilers.

- If the house with a system boiler has solar panels they can be used to heat the water stored in the tank that holds the hot water. This could be a good way to reduce monthly bills.

Negatives of System Boilers

- Due to the hot water being stored in a tank when the a lot hot water is used to run a bath etc. Sometimes the water may not always be hot because once the tank has been emptied it takes a while for the water to heat back up.
- The hot water tank needs to very well insulated to help minimise the amount of heat loss. By reducing the amount of heat loss equates to less amount of wasted energy resulting into lower energy bills.
- System boilers are bigger than combi boilers therefore require more space to be stored. This is because of the need of a hot water tank.

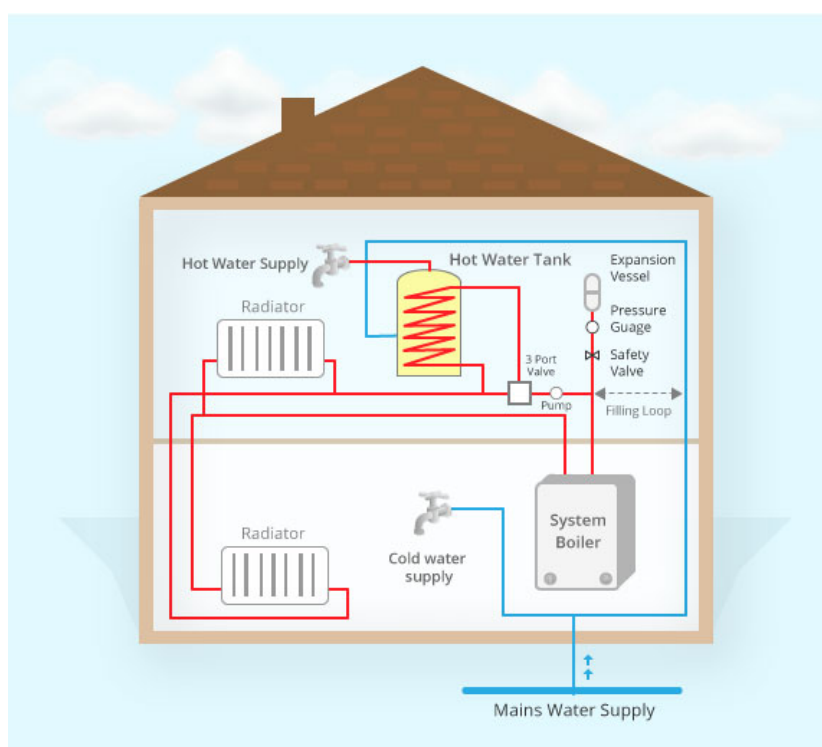


Figure 6 – How a System Boiler Works Diagram

4.2 – Warm Air Central Heating Systems

There are three main types of warm air heating systems that can be used to heat a home.

- Gas fired
- Air source heat pumps
- Ground source heat pumps

A warm air heating system uses a vent to pull in heat from the outside air and heats it over a gas flame. This warm air circulates via ducts, vents or grills which are located throughout the home. These heating systems are often managed by a thermostat. Warm air heating are modern air systems and extremely popular in countries with warmer climates due to their ability to them having electronic controls allowing to transfer a range of temperatures from 15°C to 25°C. In the UK the comfortable room temperature is 18°C to 21°C so this increases the popularity of warm air temperature systems due to them operating in the optimum temperature [11] [12].

4.2.1 – Gas Fired

Read points 4.1.1, 4.1.2, 4.1.3 and 4.1.4 for information.

4.2.2 – Air Source Heat Pumps

Heat is taken in from the air and is absorbed at low temperature into a fluid. This fluid then passes through a compressor where its temperature is increased, and transfers its higher temperature heat to the heating and hot water circuits of the house.

Air source heat pumps uses the principle of vapour compression. The vapour compression cycle is used in many products for refrigeration. A refrigerant flows through a compressor which increases the pressure of the refrigerant, it then flows through a condenser pot where it condenses from a vapour to a liquid state releasing heat in the process. The heat that has been released in the condenser makes the condenser hot to touch. Leaving the condenser the refrigerant passes through an expansion valve where a pressure drop occurs before it enters the evaporator. Within the evaporator the heat from the refrigerant is drawn resulting in the refrigerant vaporizing. The cycle can then start again as the refrigerant vapour is passed through the compressor [13]

Regarding to air source pumps there are two different types:

Air to water

An air to water system deliver heat via the wet central heating system. The efficiency of the heat pumps at a lower temperatures is low compared with a standard boiler system because they have to work harder. “This makes them more suitable for underfloor heating systems or larger radiators, which give out heat at lower temperatures over longer periods of time” [14].

Air to air

An air to air system delivers warm air which is circulated by fans to heat a home. The likelihood of them delivering hot water is low [14].

Positives of Air Source Heat Pumps

- Due to the advance technology they provide a low carbon footprint resulting in money saving on monthly energy bills.
- In the winter months they are used as heating whilst in the summer months they can be used to cool the home.
- No water tanks or fuel storage needed.
- If probably serviced twice a year the units have the potential for a long life span.
- Can be used to heat the home as well as the water.

Negatives of Air Source Heat Pumps

- When in operation the units can become noisy which could cause an issue especially at night.
- Units are expensive to purchase and install compared to other sources of central heating.
- Compared to using radiators the heat output is significantly lower.

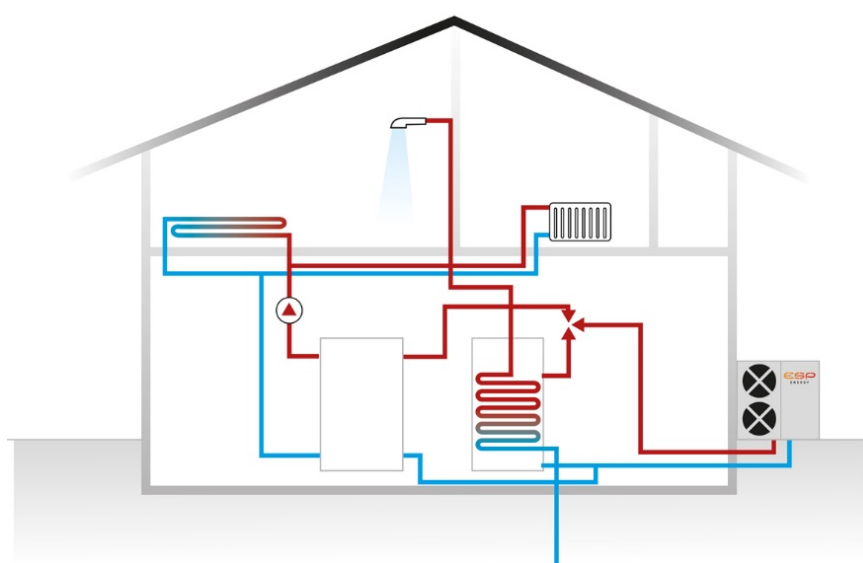


Figure 7 - How an Air Source Heat Pump Works

4.2.3 – Ground Source Heat Pumps

The association of ground source heat pump (GSHP association) state that a ground source heat pumps works by the following statement.

“Radiation from the sun heats the earth. The earth then stores the heat and maintains, just two metres or so down, a temperature of around 10°C even throughout the winter. A ground source heat pump uses a ground heat exchange loop to tap into this constantly replenished heat store to heat buildings and provide hot water.” [15]

Ground source heat pumps aren't that popular in the UK but countries such as North America, Sweden, Germany and Switzerland they have been widely used for years. Compared to installing combi boiler for example GSHP cost more to install, but with the low maintenance costs, reliability and zero carbon emissions more and more GSHP are being installed. [15]

Positives of Ground Source Heat Pumps

- Through government schemes such as the 'Renewable Heat Incentive' (RHI) provide financial aid to households that already have a ground source heat pump. For a four bedroom house it could be estimated to be worth up to £2,750 a year. [16]
- Electricity is needed to power the pump that circulates the liquid in the ground loop. Every four units of heat uses one unit of electricity used by the pump, which is used to make heat. This is what makes GSHP very efficient.
- There is no combustion therefore eliminates the possibility for dangerous gases entering the home.
- With GSHP being non visible, quiet and safe planning permission is not needed to install a unit. [17]

Negatives of Ground Source Heat Pumps

- Disruptive construction – the groundworks required to dig the trench can be expensive and disruptive – planning permission may be required if space is at a premium and you need a borehole.
- Expensive installation – installing a ground source heat pump is expensive: typically £10,000 to £18,000, depending on the size of the system (not including the cost of fitting underfloor heating, if required), according to the EST.
- Requirements – they are generally not suitable for properties with existing gas-fired central heating. The technology works at lower temperatures, making it better suited to homes with underfloor heating or very large radiators.

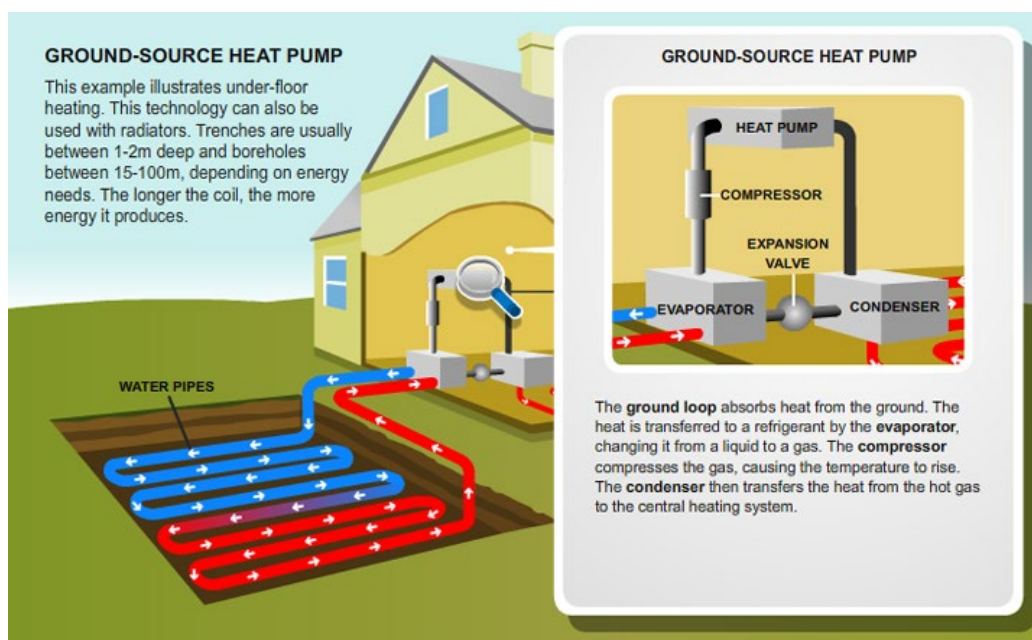


Figure 8 - How a GSHP operates.

4.3 – Market Investigation/Research Conclusion

As displayed in the market research that has been done it can be clearly seen that all of the existing products that are available can do exactly the same as this project is proposing. Neither of the products are similar to the proposed project due to this project is using an immersion heater to heat the water. The proposed system is to have a hot water tank which is heated by an immersion heater, then the water would be pumped through copper coils which are acting as a radiator. To compete with the current market this product should try and budget about £1000.

4.3.1 – Solution Requirements

In order for the project to be a success, the system is required to supply the following:

- To create a prototype of a central heating system so that it could have the potential to be implemented elsewhere.
- Make use of the temperature sensor by mounting it in the correct position in the box so that a accurate reading can be achieved and fed back to the PLC via 4-20mA.
- If the temperature of the room was to exceed a certain setpoint the PLC would need to trigger warnings and alarms via a HMI display indicating the user that an system shutdown is close to occurring.
- If the temperature was to enter a dangerous value the PLC would need to shutdown the system by switching the source of heat off and stop the pump from running.

4.3.2 – Solution 1

The temperature sensor of the room to be controlling a control valve via PID control from the PLC. The PLC would be sending out a 4-20mA signal to the positioner of the valve which would then bleed in hot water to the coils accordingly.

4.3.3 – Solution 2

For the temperature sensor of the room to be controlling the speed of the pump using PWM control from the PIC Microcontroller. This would have no need for a control valve to bleed water into the coils.

4.3.4 – Selected Solution

For this project solution 1 has been chosen. The following bullet points discuss the reasoning.

- Using a PLC a HMI module can be used to visually display the operation of the project.
- Using the PLC software TIA13 a lot more features are available such as function blocks like counters, timers and one shots etc.
- With the prototype not being on a massive scale to control the amount of water flowing just by controlling the speed of the pump would prove to be extremely difficult.

4.4 – Hardware Research

For this project to be a success the correct equipment is needed. Research into the specific sensors and other items of hardware will follow. By performing research it helps to identify the correct equipment needed and also if the hardware fits the specification requirements for the project. Below are the items of hardware needed to be researched.

- Immersion Heater
- Temperature Sensor
- Level Sensor
- Water Pump
- Water Tank
- Control Valve
- Valve Positioner
- Programmable Logic Controller

Each bullet point has been narrowed down to 4 possible items of equipment, further research is then taken place to identify which sensor is being used.

4.4.1 – Ways to Heat Water

Tesla Copper Immersion Heater Element.

To heat the water an immersion heater could be used. The electric water heater could be mounted inside the water tank. It will be powered by 230V and switched on via a contactor which would be called in and out by the PLC. One of the main focusing points that needed to be taken into consideration for deciding on a suitable immersion heater is the water hardness in the area.



Figure 9 - Tesla Heating Element

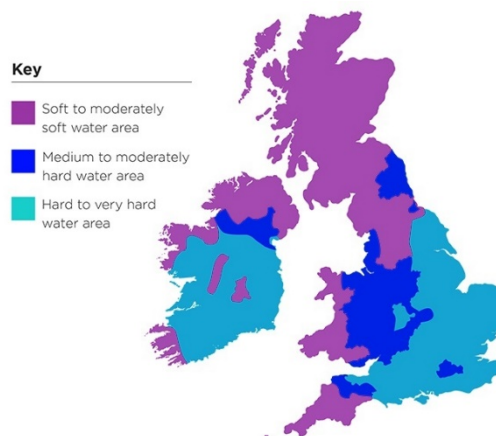


Figure 10 - UK Water Hardness Map

Figure 9 displays a map of the UK shaded in 3 colours clearly identifying the hardness of the water. As shown the majority of Wales and Scotland have soft water. Soft water is a lot better to have compared to hard water due to a number of reasons such as soft, shiny hair and skin, cleaner and shiner silverware and glassware, cheaper heating during cold winters and softer and more comfortable clothes [18]. What determines if an area gets soft or hard water all depends on the natural filtration through rock faces. As stated by a water science school “The simple definition of water hardness is the amount of dissolved calcium and magnesium in the water” [19]. As shown by figure 9 an area such as London has hard to very hard water. This is due to London being a confined built up city with no natural filtration through granite or soils, instead the rain water filters across the ground gathering high amounts of calcium and magnesium then enters the city’s water system.

By deciding to use a copper alloy as the material for the immersion heater, copper parts can’t be mounted inside a stainless steel tank due to an electrolytic reaction would occur causing the copper parts to corrode, if a stainless tank had to be used the manufacturer recommends using an Incoloy or titanium element [20].

The copper immersion heater will be mounted to the side of the tank. To create a good seal against a round tank a brass bulk head fitting is required. The heater requires 230V to operate. The PLC would be switching a 24V relay which would then switch a 230V contactor. The heater would be either on or off. No control action needed.

Solar Evacuated Tubes.

The evacuated tube collector consists of a number of rows of parallel transparent glass tubes connected to a header pipe and which are used instead of the blackened heat absorbing plate. These glass tubes are cylindrical in shape. This creates the angle for the sunlight which is always perpendicular to the heat absorbing tubes which allows these collectors to perform well even when sunlight is low. Certain parts of the day such as first thing in the morning and late afternoon or even weather conditions such cloudy days. Evacuated tube collectors are particularly useful in areas with cold, cloudy wintry weathers [21].

Evacuated tube collectors are made up of multiple transparent glass tubes in parallel with each other in bedded on a frame. Each tube could vary in diameter ranging from 25mm to 75mm and 1500mm to 2400mm. Each tube has a thick glass outer tube and a thin glass inner tube. The inner tube is coated with a material so that it absorbs solar energy and doesn't allow for heat loss. The tubes are constructed from borosilicate which has a number of good properties such as its resistant to high temperatures, high transmittance of solar radiation and is a strong and malleable material.

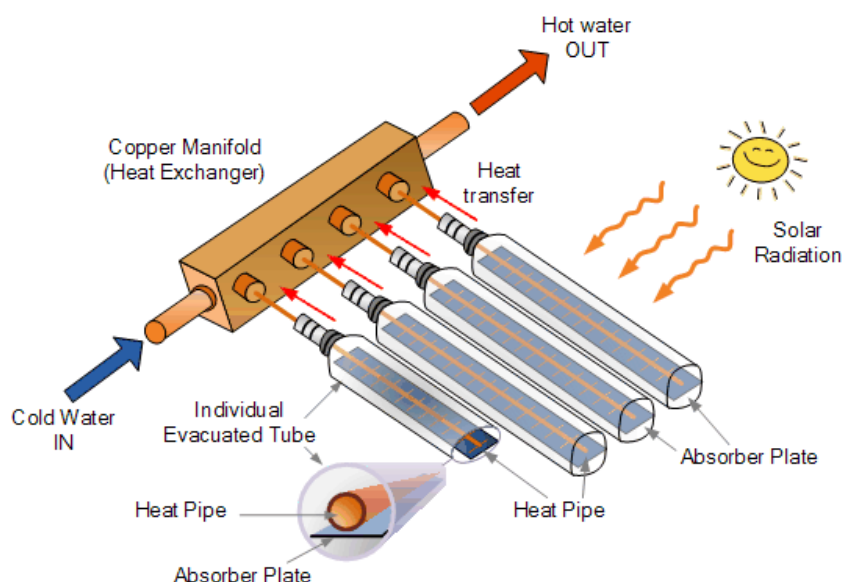


Figure 11 - How Solar Evacuated Tubes Operate

Each of the glass tubes contain a flat or curved aluminium or copper fin which is attached to a metal heat pipe running through the inner tube. The fin is covered with a special coating that transfers heat to the water that is travelling through the pipe. "The sealed copper heat pipe transfers the solar heat via convection of its internal heat transfer fluid to a "hot bulb" that indirectly heats a copper manifold within the header tank." [21]. The copper pipes are commonly all connected to a manifold which is then connected to a storage tank therefore heating the hot water during the day. If the tank is well insulated the hot water could be used at night.

Solar evacuated tube collectors are on the whole more modern and more efficient compared to the common standard flat plate collectors due to their capability to extract more heat out of the air on overcast days and do not need direct sunlight to function. Due to the inside of the glass tube being under a vacuum the total efficiency is greater therefore a much more improved performance even when the sun is not in direct

contact and at the correct angle. There are many different types of solar hot water tube configurations such as direct flow, double wall tube, single wall tube and heat pipe. All these configurations circulate the water in different ways, it all depends on the conditions with which method to use.

To purchase an evacuated tubes would cost about £500 and then labour costs to fit the unit.

4.4.2 – Ways of Measuring Temperature

Resistance Temperature Device (RTD PT100)

By using a 3 wire RTD great accuracy can be achieved. Two RTD's would be used in this project the first one being mounted inside the water tank measuring the temperature of the water. Secondly a RTD would be mounted in the box where a room would be simulated. This temperature probe would be controlling the position of the control valve to allow the water through eventually heating up the box to the desired temperature.

The Carel PT100000A1 has the perfect operating range compared to the other type of temperature measurement. As stated on the datasheet accuracy of $\pm 0.8^{\circ}\text{C}$ can be achieved making it extremely accurate [22].

With the range of the RTD being from -50 to 250°C the output resistance would be 80.3Ω to 194.1Ω .

Resistance Temperature Devices (RTD) are very common amongst all types of industry from car manufacturing to steel making for measuring temperature. A RTD detects temperature by the change in resistance of a material. An RTD probe is composed of a resistance element, a sheath and a form of termination. "The sheath, a closed end tube, immobilizes the element, protecting it against moisture and the environment to be measured. The sheath also provides protection and stability to the transition lead wires from the fragile element wires" [23].

In systems and applications where a RTD probe could become damaged due to the operation it is measuring a thermos well could be added to protect the probe from variables such as pressure, physical damage or corrosive solutions. Thermowells are solid metal tubes which the delicate probes can slide into and be protected.

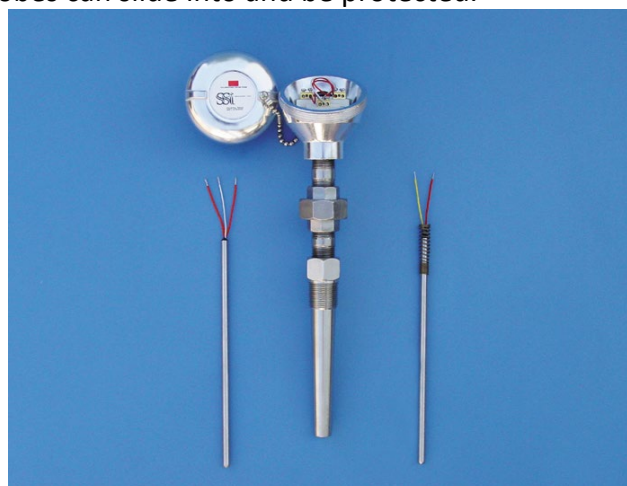


Figure 12 - RTD and Thermowell Structure

Resistance temperature devices such as an RTD have a linear output meaning that as the temperature increases as shown in figure 13.

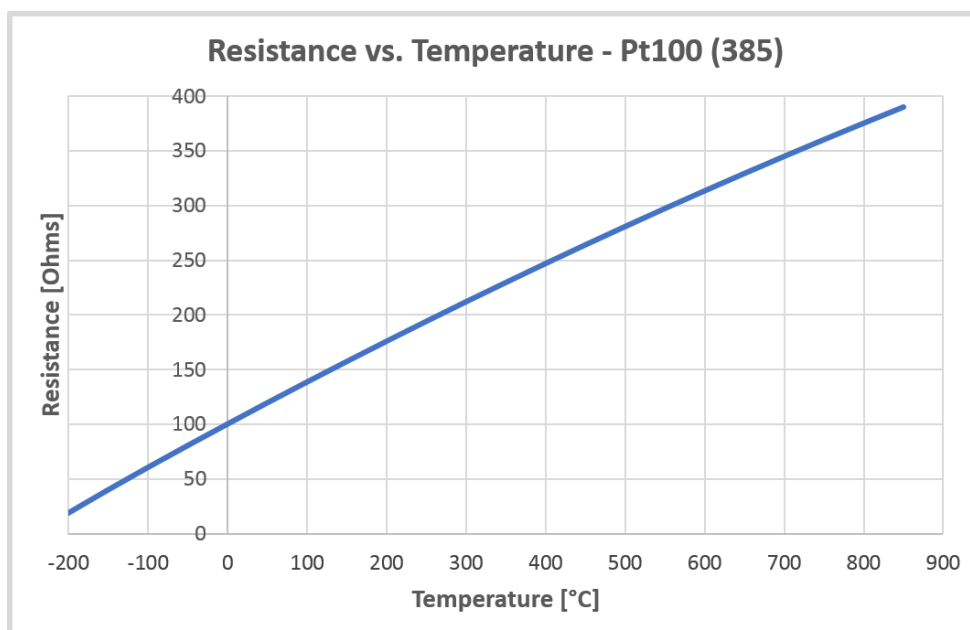


Figure 13 - PT100 Linear Output Graph

Thermocouples

Very similar to a RTD but instead of a change in the resistance a change in mV occurs. Again thermocouples are very accomplished like RTD's many different variants can be bought all depending on the temperature range required. With two wires connected at both ends of the thermocouple when heated or cooled a voltage is created that can be converted into temperature [24]. Each wire is made of two different metals and each different type of thermocouple has different metals, this is all specific to what temperature range is needed. Figure 14 displays all the different types of thermocouples and their colour coding in each country.

Thermo-couple	Material (+ / -)	Class 1 Tolerance	Class 2 Tolerance	Class 3 Tolerance
Type E	Chromel / Constantan	-40 to +375 : $\pm 1.5^{\circ}\text{C}$ +375 to +800 : $\pm 0.4\%$	-40 to +333 : $\pm 2.5^{\circ}\text{C}$ +333 to +900 : $\pm 0.75\%$	-200 to -167 : $\pm 1.5\%$ -167 to +40 : $\pm 2.5^{\circ}\text{C}$
Type J	Iron / Constantan	-40 to +375 : $\pm 1.5^{\circ}\text{C}$ +375 to +750 : $\pm 0.4\%$	-40 to +333 : $\pm 2.5^{\circ}\text{C}$ +333 to +750 : $\pm 0.75\%$	N/A
Type K	Chromel / Alumel	-40 to +375 : $\pm 1.5^{\circ}\text{C}$ +375 to +1000 : $\pm 0.4\%$	-40 to +333 : $\pm 2.5^{\circ}\text{C}$ +333 to +1200 : $\pm 0.75\%$	-200 to -167 : $\pm 1.5\%$ -167 to +40 : $\pm 2.5^{\circ}\text{C}$
Type N	Nicrosil / Nisil	-40 to +375 : $\pm 1.5^{\circ}\text{C}$ +375 to +1000 : $\pm 0.4\%$	-40 to +333 : $\pm 2.5^{\circ}\text{C}$ +333 to +1200 : $\pm 0.75\%$	-200 to -167 : $\pm 1.5\%$ -167 to +40 : $\pm 2.5^{\circ}\text{C}$
Type R & Type S	Platinum-Rhodium / Platinum	0 to +1100 : $\pm 1^{\circ}\text{C}$ +1100 to +1600 : $\pm (1^{\circ}\text{C} + 0.003^{\circ}\text{C} \cdot (t^{\circ}\text{C} - 1100^{\circ}\text{C}))^{\circ}\text{C}$	0 to +600 : $\pm 1.5^{\circ}\text{C}$ +600 to +1600 : $\pm 0.25\%$	N/A
Type T	Copper / Constantan	-40 to +125 : $\pm 0.5^{\circ}\text{C}$ +125 to +350 : $\pm 0.4\%$	-40 to +133 : $\pm 1^{\circ}\text{C}$ +133 to +350 : $\pm 0.75\%$	-200 to -67 : $\pm 1.5\%$ -67 to +40 : $\pm 1^{\circ}\text{C}$
Type B	Platinum-Rhodium / Platinum-Rhodium	N/A	+600 to +1700 : $\pm 0.25\%$	+600 to +800 : $\pm 4^{\circ}\text{C}$ +800 to +1700 : $\pm 0.5\%$

Figure 14 - Thermocouple Selection Chart

In heavy industry such as steel making for example type T is most commonly used for the lower temperature systems and type K is used for the high temperature systems. As figure 14 shows that type T consists of materials copper and constantan, copper being the positive wire and constantan being the negative wire. Type T cable is rated to go as low as -200°C and as high as $+350^{\circ}\text{C}$. Thermocouple probes look identical to RTD probes so when in the field it's hard to identify which is which so a worldwide colour identification chart was created.

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K	NICKEL-CHROMIUM	NICKEL-ALUMINUM (slightly magnetic)	32 to +2012	-292 to +2462							Wide range and most commonly used. ANSI/ASME Type "K" replaced circular 561
V	COPPER	COPPER-NICKEL									Color coded for use as a compensating cable for Type "K" thermocouples. This compensating cable can also be used for Type "T" thermocouples.
T	COPPER	COPPER-NICKEL	-301 to -572	-482 to +752							Many low temperature and cryogenic applications. Suitable for use in a mildly oxidizing or reducing atmosphere as an unprotected thermocouple sensor.
J	IRON (magnetic)	COPPER-NICKEL	+68 to +1292	-292 to +1382							Commonly used in the plastics molding industry. Not for use at low and oxidize at high temperatures.
E	NICKEL-CHROMIUM	COPPER-NICKEL	32 to +1472	-							Highest thermal EMF output change per degree F. Suitable for use in a vacuum or mildly oxidizing or reducing atmosphere as an unprotected sensor.
N	NICKEL-CHROMIUM NICKEL	NICKEL-SILICON MAGNESIUM	32 to +2012	-454 to +2372							This combination shows good promise as an alternative to Type "K". Appears to be more stable and longer lived.
R	PLATINUM- 10% RHODIUM	PLATINUM	32 to +1600	-58 to +3092							Used for high temperature applications. Has a high resistance to oxidation and corrosion. Easily contaminated and normally requires protection.
S	PLATINUM- 10% RHODIUM	PLATINUM	32 to +2822	-58 to +3092							See Type "R" above.
B	PLATINUM- 30% RHODIUM	PLATINUM- 6% RHODIUM	+212 to +2912	+122 to +3182							See Type "R" above. Commonly used in the glass industry.
U	COPPER	COPPER- LOW VALUE NICKEL									This is a compensating cable only and is used with Types "R" and "S" measuring thermocouple sensors.

Figure 15 - Thermocouple Identification Chart

As figure 15 displays all the colour codes for all possible thermocouples types in either in the United States, United Kingdom, Germany, Japan or France.

Advantages

- Cheap to purchase.
- Good accuracy achieved.
- Large selection of different temperature ranges.

Disadvantages

- Hard to identify due to colour scheme being similar in some countries.
- Due to the thermocouple being made up of two metals this makes the thermocouple vulnerable to corrosion.
- If a thermocouple breaks within its element it cannot be fixed, a new one has to be purchased.

4.4.3 – Circulating Pumps

Circulation Pumps

By using circulating pumps this keeps hot water moving through the system constantly. Circulating pumps circulate gases or liquids in an open or closed loop circuit. They are most commonly found in heating systems. They are normally electrically powered centrifugal pumps. There are only 2 main components to a circulating pump which are support bearings, the motor rotor and the pumps impeller. When the pump is asked to start the motor rotor powers the impeller which then pushes water forward. The impeller spins fast to push water out whilst compressing it. With the motor being in a waterproof casing which is directly connected to the impeller [25].

Jass Ferry Central Heating Pump KBD25-6S-130 1-1/2"



Figure 16 - Jass Ferry Central Heating Pump

The above photo is a circulating pump found on the website 'Amazon'. It is perfect for central heating systems. It has 3 speed settings and requires 230V to operate. With suction and discharge fittings measuring at 1-1/2 inches on unions it can easily be made to the required fittings. It costs £34.99 excluding the delivery charge. [26]

Lowara Ecocirc Premium 32-4/180



Figure 17 - Lowara Ecocirc Premium 32-4/180

Figure 17 is a circulation pump made from LOWARA. With its unique design using a spherical rotor the permeant magnet rotor/impeller unit is the only moving part. Spherical motor pumps are shaftless which allows them to be almost un heard for its entire working life. In case of a blocking emergency anti blocking software shakes vibrate the rotor hopefully

releasing the blockage [27]. The motor requires 230V at 50Hz to operate and costs £182.40 from the website PUMPS[UK]ONLINE.

DAB Evosta 40-70/130 Circulating Pump



Figure 18 - DAB Evosta 40/130 Circulation Pump

The Dab Evosta circulation pump is a low energy consumption electronic pump for circulation hot water for domestic purposes. Due to it having a permanent magnet synchronous motor optimum efficiency and minimum energy consumption can be achieved. It has a 3 speed motor which operates at 230V at 50Hz. Costs £92.17 on MKM Building supplies. [28]

4.4.4 – Low Water Level Protection

Water Level Switches

Within this project if the water level was to go causing the immersion heater to not be fully submerged this could cause damage and become a potential fire hazard. If an immersion heater isn't fully submerged it could cause damage to the heater resulting in a much less operating efficiency [29].

Cable Float Switch



Figure 19 - Industrial Cable Float Switch

The above float switch designed for controlling levels in large storage tanks which indirectly be installed to control pumps. By having a HDPE (High Density Polyethylene) mould it could cope with high temperatures and also corrosive substances. The switching element involves a micro switch which is activated by a stainless steel ball moving across the electrical connections. As specified in the data sheet this switch is good for 200'000 operations [30].

One unit is priced at £26.15 from RS.Components making cynergy 3 float switch a very reasonable price. The only disadvantage is that it requires 250Vac to operate.

Internal Mounted H Float Switch



Figure 20 - Nylon Float Switch

RS Components sell the Nylon float switch for £9.73 making it a very reasonably priced product. The compact internal device should be mounted inside a tank with a variety of gasket choices available to suit the needs of the operation. The switch action of the unit could be changed by rotating the switch by 180°. It comes with my different plugs such as 2 bare wires and a M12 plug. Each unit can be either be powered by 24V or 110V [31].

SPDT Stainless Steel Liquid Level Switch



Figure 21 - Liquid Level Switch

A liquid level switch operates similar to float switch as it floats in the water and once the water level falls below a certain point the internal reed switch is made. This device is very accurate as it can be easily set to a desired point. The device just needs to be raised or lowered to its correct height. The stainless steel model makes it able to operate in high temperatures and corrosive liquids [32].

4.4.4 – Valve Types

Globe Valve

Globe valves are designed to regulate flow and are primarily used for isolation and throttling services. They have a linear movement. Compared to other types of valves such as ball, gate and plug and seat a greater pressure drop is achieved therefore isn't the best type of valve if used to control flexuous gases or liquids.

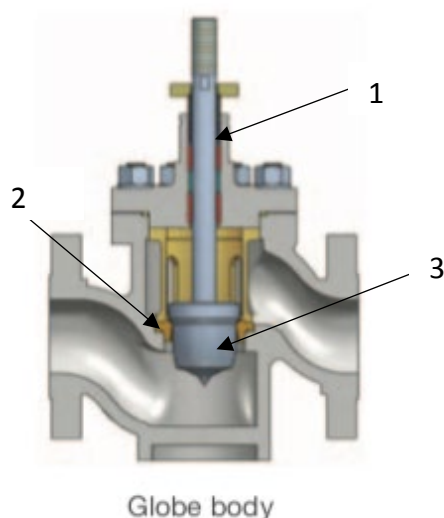


Figure 22 - Globe Valve Operation



Figure 23 - Glove Valve

A globe valves operation is moving a disc against the upstream flow instead of across its case which would then be a gate valve. The flow pattern through a globe valve involves directional changes, resulting in increased flow resistance, resulting in a drop in high pressure. The globe valve is best suited for steam operation at high pressure. Globe valves are manufactured for long term use with high quality material.

Any globe valve has a valve trim which is made up of internal parts contained by the valve body and wetted by the process. The trim could be made up from a range of materials but the most popular is stainless steel due to its hard facing properties [33]. Refer back to figure 22 which displays the following

1. Valve Stem
2. Seat Rings
3. Plug

Specially made globe valves can consist of other trim parts such as bush guides, seat retainers and spacers these all come at an added cost. The trim parts are responsible for creating the flow control and throttling restriction [33]. The trim also is key to stopping the valve from leaking the process up its stem which could create a hazard.

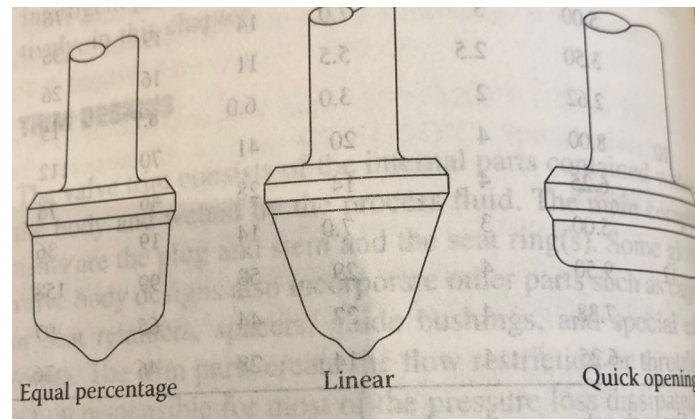


Figure 24 - Different Plug Configurations

Figure 24 shows the different types of valve plug configurations. The three different common valve plug shapes are used, all depending of the operation the valve doing.

Advantages

- Has the ability to perform tight shut off.
- Can be used effectively to throttle in against high pressures.
- Easy to repair such as machine faces and seats.
- The availability of a wide range of specialized designs for abrasive, high pressure, high temperature and corrosive substances.
- Large selection of valve characteristics.

Disadvantages

- A large pressure drop across the valve could effect process.
- A larger actuated force is needed to seat the valve because the process pressure happens under the seat.

The pricing of a globe valve varies massively with specially machined valves cost as much as £4000 but the price of figure 23 is £94.04 from the website 'Actuation Valve' due to the body being made out of cast iron [34].

Ball Valves

A rotary ball valve is one of the best on/off valves and are widely used across the world. Compared to globe valves they cost a lot less, weigh less and have a greater flow capacity. Many ball valves have different designs and different characteristics.

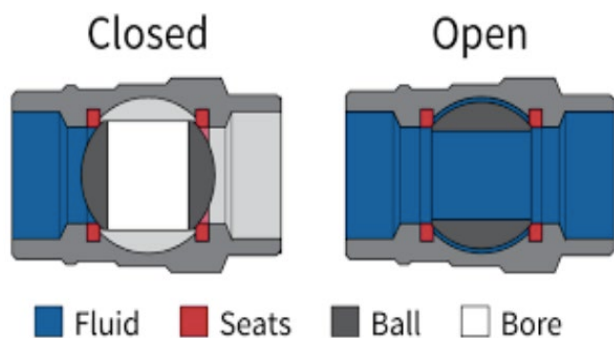


Figure 25 - Internal Ball Valve Diagram



Figure 26 - Kelm K Actuated Ball Valve

The popular quarter turn (90°) when manually operated fully either has the bore of the valve fully open or fully shut. By having a spherical plug it can achieve accurate flow throughputs also tight shut off. Due to tight shut off being critical in some processes special materials are used for the valve seats and balls. Ball valves can also be used as block valves because they don't allow the process to pass the valve when shut [35]. Below is a diagram clearly displaying how the process flows when the ball valve is either fully open, throttled or fully closed.

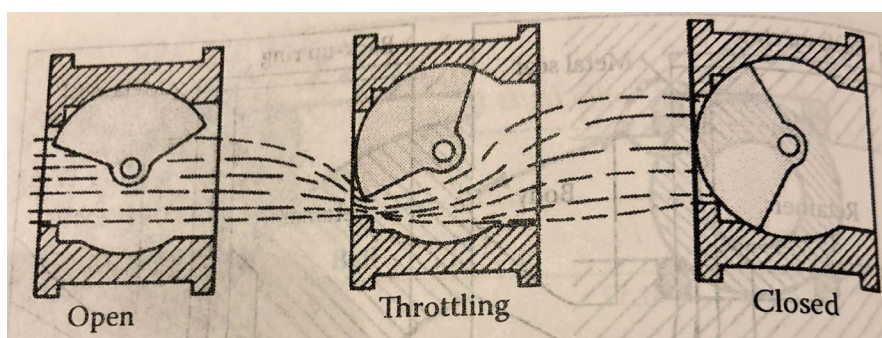


Figure 27 - Process Flow at Different Ball Valve Positions

As can be seen in figure 27 that 100% of the process flow can pass through when the ball valve is fully open. When the ball valve is in the 'throttled' position a pressure drop is created due to only a partial amount of process can be passed through. When the valve is fully shut 0% of the process is passing through and a tight shut off is achieved. This can be used as block valve for isolation purposes.

The characteristics of a ball valve can either be "V notched, U notched, parabolic and anticavitation/ anti noise designs" [35]. Notched valves and partial ball valves were created to prevent the valves from clogging up therefore tight shut off could not be achieved. Due to these valves becoming so popular and versatile due to their increased rangeability and shearing motion.

The trim used in a ball valve only consists of the stem, body, ball and seals. The ball within the valve is cradled by seats on both the inlet and the outlet of the valve. The seats are made up of PTFE and are reinforced by metal seats to achieve tight shut off. Quite commonly the PTFE seats get damaged which is caused by high temperature [35].

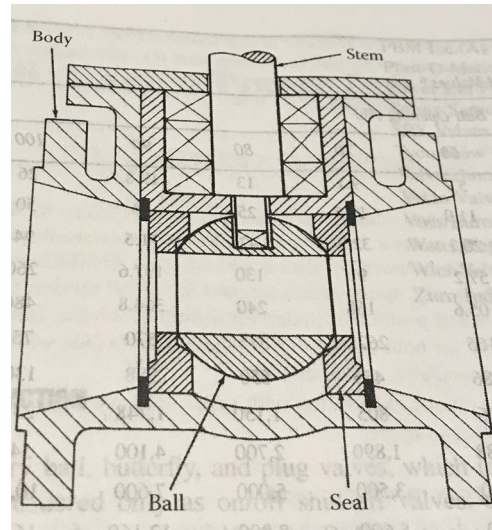


Figure 28 - Ball Valve Trim Diagram

Advantages

- They are extremely durable and are recognised for their ability to last many years delivering a reliable service.
- Extremely cheap to purchase and to repair compared to other types of valves.
- Require very little lubrication due to their PTFE seals.
- Are easy to install and operate as they are very commonly only a 90 degrees rotation.
- Can handle very high pressures and flows.

Disadvantages

- Due to them being able to be used on almost any process ranging from cryogenic liquids to corrosive substances ball valves are very common to wear and tear so constant maintenance is needed.
- In the throttling position the seats are exposed to the process which would erode the seats causing the valve to become damaged. Ball valves should either be fully open or fully shut.

Plug and Seat Valves

Quite similar to ball valves but with plug and seat valves greater control can be achieved due to the quick response of its design. Plug valves are well suited for such applications such as low flow control, high or low temperature control and high flows at low pressure drops [36].



Figure 29 - Fisher Plug and Seat Control Valve

Figure 29 shows a plug and seat Fisher GX Control Valve. With it being a plug and seat valve its extremely good in control systems which either require quick opening or closing with tight shut off. They have very good response time.

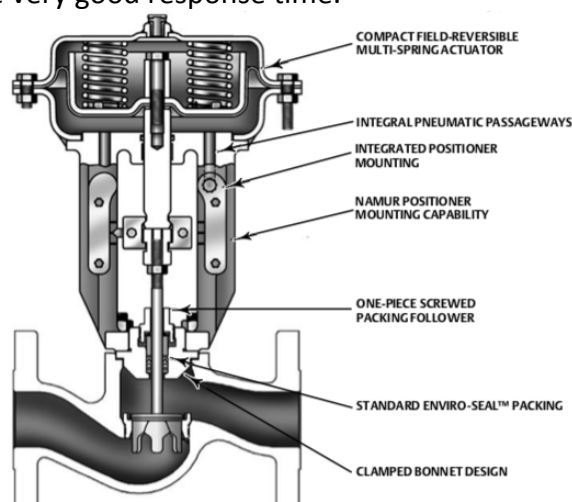


Figure 30 – Fisher GX Control Valve Inner Workings

The fisher GX valve has a spring return actuator. This means that with no air pressure on the valve the actuator will either open or shut all depending of the setup of the valve. For example, if the valve was configured to be air fail shut, if the supply pressure or power had either failed the valve would shut creating a tight seal preventing the process from escaping. For it to be a control valve a positioner needs to be mounted onto the valve, this would then either open or shut the valve to any point of the full travel within the stem.

Overtime plug and seat valves have developed into many different shapes and patterns all depending on the process its operating in but most of the adaptations are either tapered or a cylindrical plug [36]. Inside the plug the ports could be round, V shaped, rectangular or diamond shaped. Plug and seat valves are separated by either lubricated or non lubricated. The lubricated slowly emit lubricant into the valves packing to reduce the amount of friction between plug and the valve body. It also creates a compressed seal which stops the process gas or liquid leaking up the stem. Regularly the lubricant needs to be injected into the valve packing so that the valve doesn't start to wear or seize.

Advantages

- They have a simple design with few parts to fail meaning that maintenance costs are low.
- To perform maintenance the valve doesn't need to be removed from service and repairs can be performed in place of operation.
- Lubricated valves have a very good seal around the plug eliminating the process leaking past the plug.
- Excellent control can be achieved especially with low flows.

Disadvantages

- Wear and tear on the internals of the valve can occur quite quickly if the seat material fails causing the valve to pass.
- They cost much more compared to other types of valves due to the accuracy that can be achieved.
- Larger valves would require extra torque to operate so an actuator is sometimes needed.

Butterfly Valves

Very much like globe and plug valves butterfly valves are used as throttling control valves. Butterfly valves are well suited for applications where high volumes and flow rates are needed.

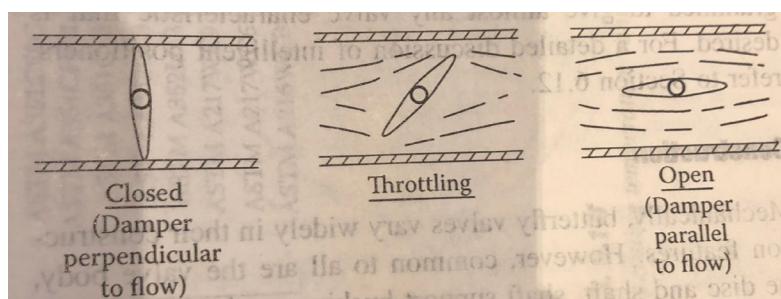


Figure 31 - Butterfly Valves Operation

Figure 31 displays the disc position when the valve is closed, throttled and open. The disc is only a 90° rotation. The operation of a butterfly valve isn't complex as it's only a rotating vane or paddle which is connected via a shaft that is tightened by the linkages. The shaft could either be rotated by a manual wheel or an actuator. For the best control a pneumatic actuator should be fitted to give 0 – 100% rotation. The construction of butterfly valves can vary but what is common between all butterfly valves are the valve body, bearings, disc (paddle), shaft and shaft packing. Butterfly valves split into two categories, 'swing through' and 'shut off'. The most common design in industry are the 'swing through' as shown in figure 32 identifying all the trim components.

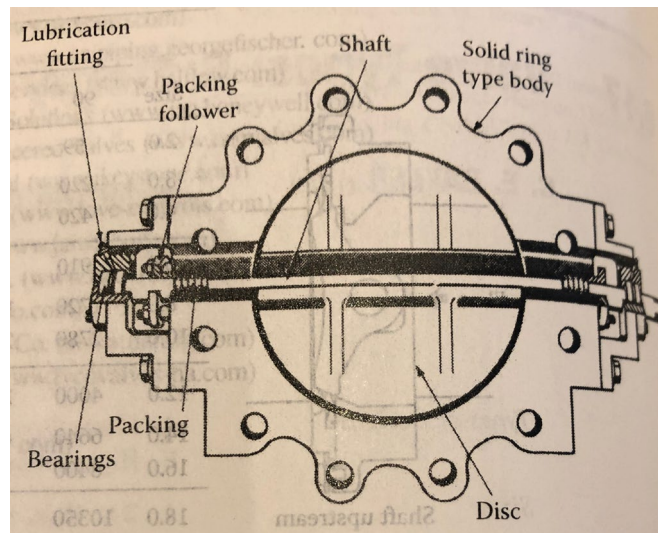


Figure 32 - Internal Design of a Swing Butterfly Valve

The disc is casted into one solid part and the material all depends on the process it would be operating against. The disc could be coated with a hard material if exposed to corrosive or cryogenic substances. The valve is flanged into pipework and is bolted through the body to tighten up all the components trying to reduce the amount of flange leakage [37]. The maximum travel of butterfly valves tend to be between the 60° and 70° rotation due to there being mechanical stops inside the valve preventing the disc from over rotating. After the valve being 70° open the max throughput is achieved therefore the valve doesn't need to open any further.

Advantages

- Cost less compared to other valves.
- Weigh much less compared to other valves so are much easier to install and remove for maintenance.
- Have capable of up to 3 times the flow capacity of globe valves.
- Low stem leakage.

Disadvantages

- Due to their high capacity properties companies tend to install either oversized valves or small valves in large pipework.
- To achieve linear rotation actuators are needed and are connected via linkages meaning that some percentage of the open or closed signal would be lost through tightening up of the linkages [37].

4.4.5 – Valve Actuators

To achieve precise control of processes such as temperature, flow, pressure and level control valves all require an actuator and a positioner to mechanically move a valve to any position between 0 – 100%. When deciding on an actuator a 'piston' or 'spring and diaphragm' types need to be considered. The main reason of which type to select comes down to what failure state the valve needs to be. With spring and diaphragm actuators all depending on weather the springs are located the valve can be made to fail open or fail close.

For the valve to fail open the springs are located under the diaphragm so that if the air supply to the actuator failed the springs would force the diaphragm up therefore venting out the closed air resulting in the valve driving open. The opposite would happen if the springs were located above the diaphragm, driving the diaphragm down closing the valve. These conditions are known as either 'air fail open' or 'air fail closed'. As Fisher Actuators show in their user manual described by figure 33 below.

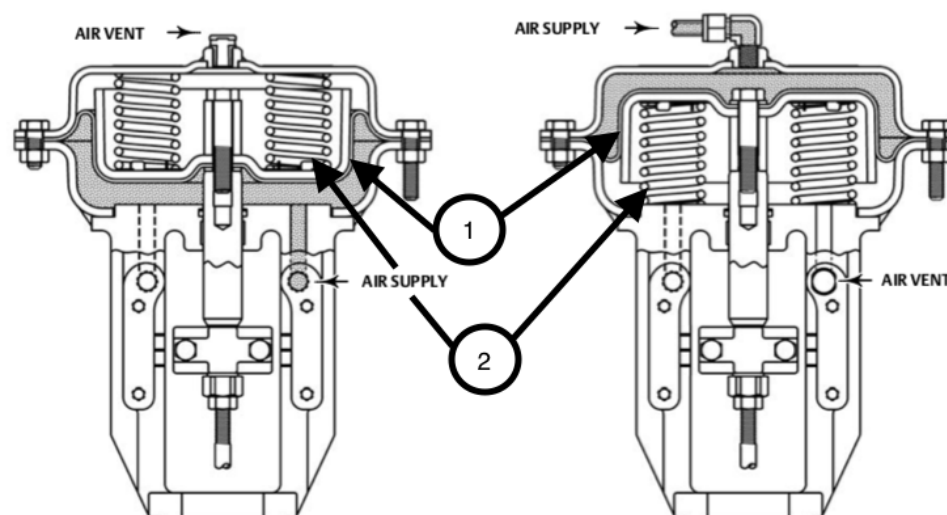


Figure 33 - Fisher GX Actuator Air Fail Configurations

1. Diaphragm – Constructed out of material such as rubber or PTFE.
2. Acting Springs – Constructed from hardened metals or none ferrous metals.

The left diagram of figure 33 shows the diaphragm below the springs meaning the valve would be air fail closed whilst the right diagram shows the diaphragm above the springs meaning the valve is air fail open.

Piston actuators are purchased as either single or double acting. Single acting is where the valve has a fixed air supply directed onto only one side of the diaphragm resulting in either open or closed and a spring returns it to its original state whereas double acting actuators have air supplied on both sides of the diaphragm which is controlled by a positioner as shown in figure 34 [38].

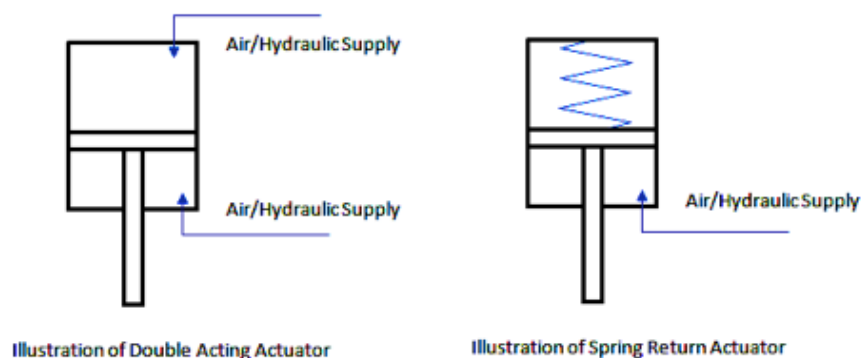


Figure 34 - Single and Double Acting Actuators Explained

4.4.6 – Valve Positioners

A valve positioner allows the valve to be controlled with a linear action meaning that any figure between 0 – 100% can be achieved. The positioner for example could have two outputs, each output being piped above and below the diaphragm. The positioner would have a input I/P converter which means an electronic signal would be converted to a pressure signal. Example, 4-20mA to 3-15psi. That pressure is then directed to either side of the diaphragm either opening or closing the valve. The electronic signal is directly proportional to the air output signal so as the mA's increase so does the psi. For the positioner to work correctly it needs to be configured with the valve so that when the electronic signal is at 4mA the valve is fully shut and when the signal is 20mA the valve is fully open vice versa. To adjust the positioner zero and span adjustments can be made as well as moving the position of the internal 'cam plates'.

A positioner can also provide linear feedback to a control room operator so that it can be seen exactly how far open or closed the valve actually is.

Pneumatic Positioners are also very common in industry as they don't need a

PMV P5 Analog Positioner

With a robust and simple design the PMV positioner has a long lasting life and is easy to install whilst following the user manual. The P5 has a built in IP converter and feedback so no extra modules would need to be added and calibrated. It can be suited for single and double acting configurations providing accurate control [39]. Priced at £475.70 a unit it isn't cheap compared to other positioners.



Figure 35 - PMV P5 Positioner

Advantages

- Built in IP converter so no extra module needs to be purchased resulting in more space and less wiring and piping needed.
- Easy to mount and configure meaning that its user friendly and anyone without past experience could install following the user manual.
- A lot cheaper compared to other electronic positioners.

Disadvantages

- From personal experiences the seals around the IP converter cover and the guide cover are poor quality so overtime water leaks in causing the internals to corrode eventually causing the positioner not to operate.

Valtek Beta Positioner

With no built in I/P converter the Valtek Beta Positioner is fully pneumatic and relies on the electronic signal to be converted elsewhere, unless the Valtek I/P module is purchased separately. The IP module is can be fitted very easily as only 2 bolts need to be tightened to hold the module in place. This positioner is supplied with a mounting bracket so can be easily installed. It can be used to control both single and double acting actuators [40]. Priced at £250.00 a unit it isn't cheap but it is very robust and controls valves very well once set up.



Figure 36 - Valtek Beta Positioner

Advantages

- Can achieve excellent control once set up correctly.
- Very robust and lasts long in bad weather conditions.
- Comes with mounting brackets so is very easy to attach to valves.
- Has visual gauges on both outputs and supply air which is very useful for fault finding.
- Not too expensive as it is a very good positioner.

Disadvantages

- User manual is complicated to follow initially but with experience it becomes simple.
- Can only be mounted to a small number of valve types as the bracket supplied is specific to valves with a large stem.
- Doesn't come with a I/P converter as standard so an extra cost is needed if required.

Fisher FieldVue DCV6200 Digital Positioner

Having a solid and robust shell encapsulating the electronics and pneumatic internals the DCV6200 is very effective against all industrial conditions such as temperature and vibration. It is also protected from corrosive and erosive atmospheres. By using a HART communicating device the DCV6200 positioner can be configured making the installation and set up a lot easier for the commissioning team. The fieldvue positioner provides high performance and lightening fast response times to the smallest of changes making this positioner one of the leaders of the current market. Being priced at £909.00 this positioner is a lot more expensive compared to other positioners but for reliability and precision there is no other positioner quite like it. A lot of companies are paying the price for these positioners because if being used on a valve controlling a major process for example, accuracy and reliability are key contributing factors.



Figure 37 - Fisher FieldVue DCV6200 Digital Positioner

Advantages

- Pneumatic and electronic controls are protected from all industrial conditions due to its encapsulating shell.
- Has really quick response time due to it being able to be configured by a HART communicator.

Disadvantages

- It has an expensive price tag compared to other positioners but it worth the extra cash if reliability and precision is required.

Siemens Sipart PS2 – Electropneumatic Positioner

The Sipart PS2 electropneumatic positioner controls the last control element of pneumatic linear or part-turn actuators. The electropneumatic positioner applies air to the actuator which then adjusts the valve position corresponding to the set point. Function inputs can be used to block the valve or create a safety position. It can be configured using a HART communicator making installation much easier. It has a self-diagnostic feature meaning that if a fault occurred with the positioner an error code would be shown via the display helping to identify the fault. Being priced at £865.05 the positioner is the second most expensive positioner out of the selected 4 [41].



Figure 38 - Siemens Sipart PS2 Electropneumatic Positioner

Advantages

- Once set up and configured very rarely this positioner would experience a fault, making this positioner very reliable if probably maintained.
- Has a self set up function meaning that once the positioner has been fitted it would find its lower range and upper range value. This would then be the full range of travel for the valve.

Disadvantages

- Is quite difficult to set up without a HART communicator due to the positioner having a small display to show the different set up menus.
- With the positioner being very expensive and only compatible to some types of valves this positioner isn't very popular in the older industry compared to modern industry.

4.4.7 - Programmable Logic Controller Requirements

For this project to be successful the following PLC Requirements are needed.

Analog Inputs

- 1 x Analog 4 – 20mA for the vessel temperature.
- 1 x Analog 4 – 20mA for the room temperature.

Digital Inputs

- 1 x Level Switch.
- 1 x Start Switch.
- 1 x Stop Switch.

Analog Outputs

- 1 x Analog 4 – 20mA signal for temperature control valve.

Digital Outputs

- 1 x Pump Operation.
- 1 x Immersion Heater.
- 1 x Running Light.
- 1 x Stopped Light.

Communications

- Ethernet to communicate to the HMI

Power

Input 240V @50Hz

Output 24V DC

PLC Requirement Summary

Analog Inputs	2
Digital Inputs	3
Analog Outputs	1
Digital Outputs	4
Communications	Ethernet
Power	240V & 24V
HMI Compatible	Yes

4.4.8 – Programmable Logic Controller Type Selection

Rack Mounted

Rack mounted PLC's can have extra modules added to them once mounted so in the scenario where numbers of spare I/O are low, extra cards can be connected resulting in more channels available. With each card mounted into a rack. The rack provides power and communications between all the cards.



Figure 39 - Rack Mounted PLC Example

Advantages

- Can expand I/O if needed so can never be short of available signals.
- Can replace cards without becoming in contact with the power rails due to the mounting rack powers the cards.

Disadvantages

- Expensive to initially purchase and replace if any faults occur.
- Large unit to mount so takes up a lot of space.

Modular

A modular PLC is very similar to rack mounted PLC's due to them being able to be expanded if extra I/O is needed. With modular PLC's they can be custom built to what is required for the process to do.



Figure 40 - Modular PLC Example

Advantages

- Can be built to what is needed and can always be expanded.
- Can handle and process a lot of I/O for complicated systems.

Disadvantages

- Expensive to initially purchase and to expand.

Unitary

Unitary PLC's is a housed unit that contains all the modules in one, such as the communications, power supply and I/O. This is the most basic out of the 3 different types of PLC and the cheapest. The unit cannot be expanded and is limited to what it can handle.



Figure 41 - Unitary PLC Example

Advantages

- Are quite commonly found on electrical switchgear control circuits due to their reliability and being so robust.
- Are a lot cheaper to purchase compared to other type of PLC.

Disadvantages

- Cannot add other modules so only has a specific number of I/O.

PLC Selected

By selecting a modular type PLC it provides the chance to expand the I/O if needed and allows to keep the project small and compact rather than having a big bulky rack mounted PLC.

Model	Allen Bradley 1762 series	Siemens s7 1200 PLC	Mitsubishi FX2N Series PLC
Image			
Type	14 Inputs & 10 relay outputs	8 digital inputs, 6 digital outputs and 2 analogue inputs	Maximum 256 I/O. Up to 80 analogue inputs and 48 analogue outputs.
Positives	Rockwell's development is perceived by some as intuitive and easy to use. Siemens is perceived as extremely capable, but developed more for engineers than for maintenance and support personnel.	Once a Siemens PLC has been purchased its free to use its technical support. Siemens doesn't require a Siemens power supply whilst Allen Bradley PLC need an Allen Bradley power supply to operate.	Other types of PLC usually have limited numbers I/O modules so with added modules more complex processes can be achieved. Mitsubishi offer a good troubleshooting document which should cover every problem that could be encountered.
Negatives	If you have an issue with an Allen Bradley PLC to seek advice they charge for technical support.	Has 0 analogue outputs so n extra module is needed which cost around £1200. By assign this module it would give 2 analogue outputs.	The only drawback is that to by each module is very expensive and in total would cost a lot more than using a Siemens PLC for example.

Table 7 - PLC Comparison Table [42]

The PLC of choice is the Siemens S7 1200 series due to it being small and compact and has the correct amount of I/O needed for the project. TIA 13 programming software can then be used to write the ladder logic and build the HMI screens.

Analogue Output Module

Due to the Siemens S7 1200 PLC not having any analogue outputs an expansion module is needed which then allows room for one analogue output. The module can be purchased from RS for £91.00. This will allow for the PLC to control how much the valve is open allowing only the correct amount of hot water through.



Figure 42 - Siemens S7 Expansion AO Module

Human Machine Interface (HMI)

Having a HMI screen allows for operators to control and understand the process. The Siemens Simatic HMI is compatible with S7 Siemens PLC's making it the obvious choice to use. With the HMI being 7" wide its big enough to clearly see and operate. Having the PLC programme being constructed in TIA13 a HMI that was compatible is priority.



Figure 43 - Siemens Simatic HMI

4.4.9 – Utility Items

Non Return Valves

On the common outlet pipework from the copper coils there would be a 22mm brass non return valve preventing any water from the pump passing the wrong way through the coils. Without the non return valve the water would travel back through the copper coils resulting in the project not working because no heat transfer could take place. A non return valve only allows for a flow of gas or liquid to travel in one direction. The flow of water pushes against a spring returned pad allowing the liquid through, if it tried to travel the opposite way the spring would keep the pad shut. As shown below.

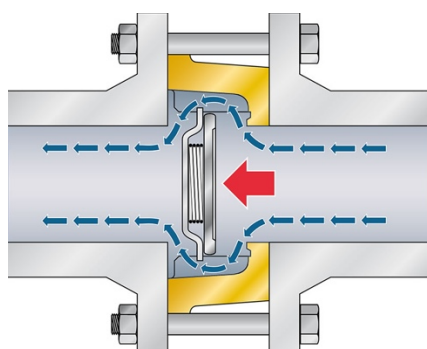


Figure 44 - Operation of a Non Return Valve

Copper Pipe and Fittings

Connecting all the equipment together would be made from 22mm copper pipe. The copper coils inside the room would be made from 10mm pipe due to being able to make more coils resulting in a larger surface area for optimum heat transfer. 22mm and 10mm brass fittings would be used such as elbows, couplings and bulkheads to keep all the pipework connected and leak free.



Figure 45 - Cooper Coils Example

Electrical Cable

For 24Vdc normal 0.75mm cable is being used as the loops it's connecting are low current. For the 3kW immersion heater the current drawn equates to

$$\begin{aligned} \text{Power} &= \text{Current} \times \text{Voltage} \\ \text{Current} &= \text{Power} \div \text{Voltage} \\ \text{Current} &= 3000 \div 230 = 13.04 \text{ Amps} \end{aligned}$$

Equation 1 - Immersion Heater Current

With the immersion heater pulling 13.04 Amps putting 0.75mm twin and earth would be unsuitable according to RS Components as shown below.

Manufactured to VDE 2050 standard

CSA	0.75mm ²	1mm ²	1.5mm ²	2.5mm ²
Conductor size	24 / 0.2	32 / 0.2	30 / 0.25	50 / 0.25
Current rating (A)	6	10	16	20

Figure 46 - RS Components Current Ratings

So by referring to the above statistics 2.5mm cable would be used to power the immersion heater as it is cable of up to 20 Amps.

Omron Power Supply

A power supply is needed to be able to power up the control circuit board as it needs 24V. The power supply would take in mains 230V and output 24Vdc. The output voltage would then be taken down to a common rail where multiple 24V supplies can be used across the circuit board.



Figure 47 - Omron Power Supply

Finder 24V Relays

Relays are extremely common when used for any control circuitry. A relay is an electromagnet that has normally open and normally closed contacts. The relay itself is just a metal coil that when energised completes the circuits connected. Relays are switches that open and close circuits electromechanically or electronically. Relays control one electrical circuit by opening and closing contacts in another circuit. Relays used to switch bigger currents, as the control voltage would be across the coil and the bigger current devices would be across the contacts. This can be seen as a way of protection of the control circuit because the control voltage would never come in contact with the bigger voltages or currents [43]. Likewise with this project due to the PLC outputs only being 24V it wouldn't be able to switch the immersion heater or the circulating pump as they both require 230V. So by the PLC switching the 24V coil the immersion heater and pump can be controlled.

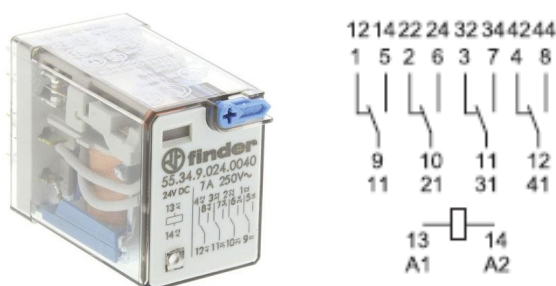


Figure 48 - Finder Relay 4 Contacts Physical and Wiring Diagram

As the wiring diagram shows within figure 48 the control voltage is supplied across the coil which is terminals 13 & 14. Terminals 9, 10, 11 and 12 is where the desired switching voltage should be supplied. This project requires normally open contacts so terminals 9 and 5 can be used to switch the immersion heater. As worked out previously the immersion heater requires 13A. The finder relay being used is only rated to switch 7A so technically isn't suitable to be used. But having confirmation from an electrical foreman at BOC Gases the immersion heater can be wired across a normally open contact, then if both sides of the relay are commended up with the 3 spare switching contacts the load is spread across 4 contacts making each switch having 3.26 Amps running through it.

A 2nd relay is being used to switch the circulating pump and the same contacts are being used but because the pump is only 76watts the pump can be wired in 0.75mm cable straight across the relay.

PR Unit 4114

A PR unit is a universal transmitter made by PR electronics. They are programmed by using a detachable display front. They accept a range of inputs such as RTD, thermocouple, current and voltage. They then provide a linearized output which could either be voltage or current. The voltage is either 1 to 5V or 0 to 10V. The current is a standard 4 to 20mA signal. The unit has a green and red LED indicating whether the unit is normal operation mode or in malfunction [44]. The 4114 model has a universal AC or DC power supply input. Many other models can have relay outputs so can be used as a trip amp.

In regards to this project two of them are being used to take in a resistance from both RTD temperatures and output a linear voltage of 0 to 10V to the PLC.



Figure 49 - PR Unit 4114 and Programming Screen

4.4.10 – Research Conclusion

From the research carried out into the hardware required to make the project successful it is vitally important to purchase the correct equipment. By researching into hardware it helps to give a better understanding of what exists on the current market, by investigating into different items of equipment the design of the project may change resulting in better operation and efficiency. To conclude the chosen hardware a brief table is shown below.

Equipment	Image	Model	Supplier	Cost £	Operating Voltage
Water Heater		Tesla Copper 11"	Plumbpoint	11.00	230Vac
Temperature Measurement		RS Pro RTD PT100 3 wire	RS Components	38.14	24Vdc
Level Switch		RS Float Series Cynergy	RS Components	9.73	24Vdc
Control Valve		Fisher Plug and Seat	BOC Gases	0.00	N/A (uses compressed air)
Control Valve Positioner		Fisher Fieldvue DCV6200	BOC Gases	909.50	24Vdc
Programmable Logic Controller		Siemens 1200	UWTSD	288.88	24Vdc
Human Machine Interface		Siemens Simatic 7"	UWTSD	600	24Vdc

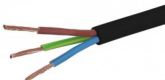
Power Supply		Omron 24V	RS Components	181.10	230Vac
Relays		Finder 4PDT	RS Components	9.55	24Vdc
Universal Transmitters		PR 4114	BOC Gases	319.42	24Vdc
Copper Pipe		22mm and 10mm	BOC Gases	80	N/A
Electrical Cable		0.75mm & 2.5mm	BOC Gases	100	N/A
Switch Box		Siemens Scalance XB005	UWTSD	N/A	24Vdc
Water Tank		N/A	BOC Gases	Free	N/A

Table 8 - Hardware Research Conclusion

4.5 – PID Control

4.5.1 – Closed Loop Operation

Within a closed loop system the controller derives its input signal by using the measured value from the output of the process. This measured value is known as feedback. Feedback allows to keep the process variable close to its desired value which is its set point. Figure 46 below shows exactly how a closed loop system works. [45]

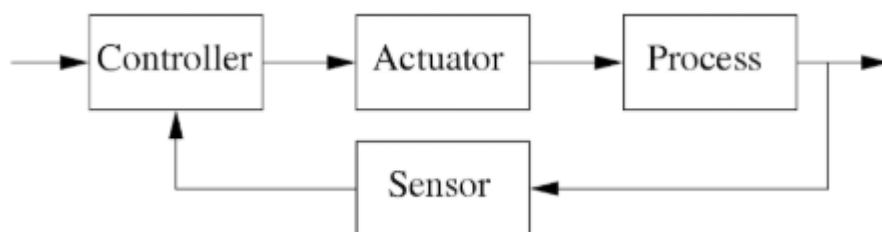


Figure 46 - Closed loop system operation

Controller Block

“The controller has an input signal which is normally an error signal based on the difference between the set point value in which the loop controls at and the feedback signal from the measured output. The feedback signal from the transducer determines the controllers following output.” [42] [45]

Actuator Block

This is where a physical action occurs to help achieve the process. For this project the actuator block would be to open or close a plug and seat valve in a linear motion to control the amount of hot water passing through the copper coils.

Process Block

The process block is the actual process variable such as the house temperature for this project trying to be controlled. [42]

Sensor Block

In regards to this project the sensor block would be a temperature transducer which is a RTD. If the feedback signal from the RTD was greater than the controller’s set point the output from the controller would tell the actuator block to start closing in to restrict the amount of hot water travelling through the copper coils.

Closed Loop Advantages

- Reduces errors by automatically adjusting the loops input signal.
- More accurate control and repeatable performance.
- Flexible control tuning.
- Improves the stability of a swinging unstable system. [42]

Closed Loop Disadvantages

- Require the use of sensors therefore increases the build cost.
- Greater complex design making it harder to build.
- Initial tuning is difficult.

4.5.2 – Open Loop Operation

The difference between an open loop and closed loop system is feedback path. In an open loop system the output signal isn't transferred back into the input of the controller. The control action is independent to how the output signal is changing.

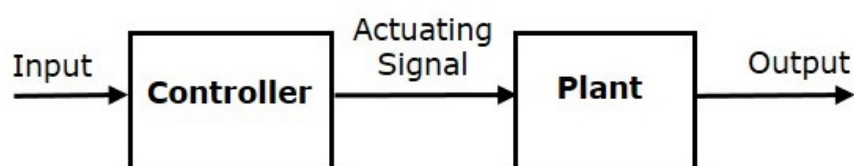


Figure 47 - Open loop system operation

Figure 47 is a diagram of how an open loop system works showing an input directed to the controller which creates a control signal which would then control a process resulting in an output. “A good example of an open loop system would be a washing machine. The washing machine would just stay on until the reset timer counts down, it doesn't look to see if the clothes have actually been washed or not.” [42]

Open Loop Advantages

- Very simple to implement and design.
- A lot cheaper compared to closed loop systems.
- Very little maintenance needed on open loop systems.

Open Loop Disadvantages

- The output can't be corrected automatically.
- Open loop systems aren't accurate compared to closed loop systems.
- No feedback.

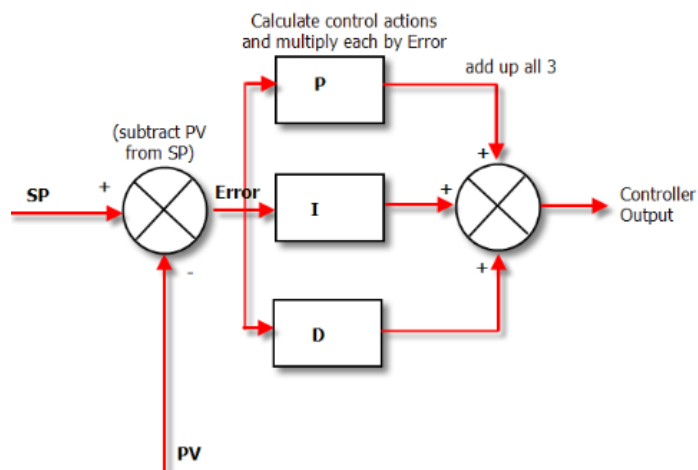


Figure 48 - Block Diagram of a PID Controller

Page 55 and 56 are both pages from my PLC Assignment which have been used to explain open loop and closed loop systems. Having tried to re-word I feel like that I can't deliver much better information.

4.5.3 – Proportional Control

The simplest type of linear control is just using the proportional action. It is created by the connection between the controllers input and output. If an adjustment is made to a controller it is either referenced as proportional band or gain.

With controllers having high gain values they tend to resemble less sensitive controllers whilst lower gain values resemble a much greater sensitivity controller setting.

The mathematical of a proportional controller is shown below.

$$m = K_c e + b = \left(\frac{100}{PB} \right) (e) + b \quad [46]$$

Equation 2 - Proportional Control

- “m” is equal to the output signal. This output signal could be to a control valve.
- “K_c” is the gain of the controller.
- “e” is the discrepancy action between the set point or error.
- “PB” is the proportional band, (100/K_c).
- “b” is the “live zero of or bias of the output which in pneumatic systems is usually 0.2bars and in analog electronic loops is 4mA.” [46]

Due to the proportional controller not identifying previous or future errors the controller can only act on its present error value. When a small error occurs a large response is caused by the controller resulting in the proportional gain increase. The opposite effect happens when a large error takes place a small response from the controller happens resulting in a smaller gain value [46].

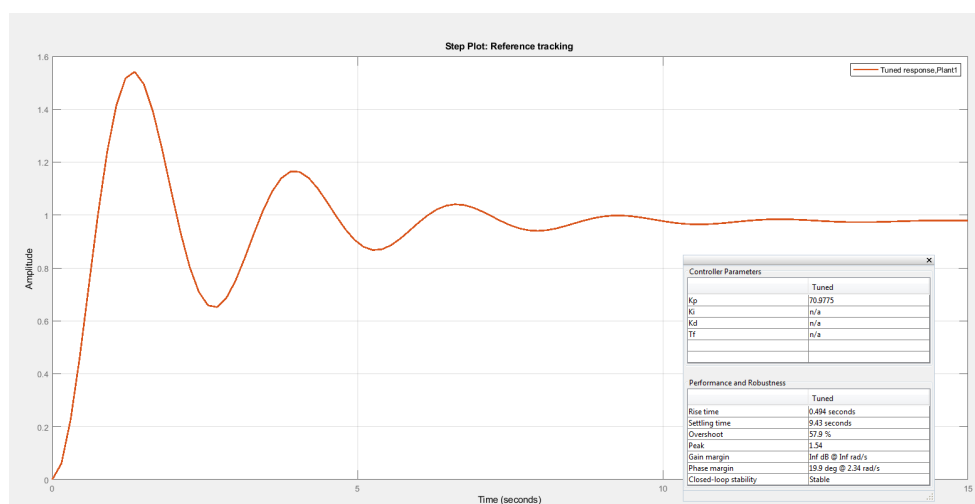


Figure 50 - Proportional Control via MATLAB

Figure 50 on the previous page is a proportional control only signal from a previous PLC assignment completed by the author of this project. It is a good example to use as it shows a small error occurring resulting in a large response causing the gain value to be high as well.

In figure 50 due to the large response the gain value reached 70.98 before the signal smoothed out and was under control. Using proportional control only the process value would never control at 1 because it doesn't allow for the process to return to its desired set point which then creates an offset. If the proportional sensitivity is high then the offset would be small. [47]

As Doebelin states "A 10% proportional band (PB) means that a 10% change in the controller input causes a full scale (100%) change in controller output." [48]

4.5.4 – Proportional and Integral Control

Reset control which integral control is commonly known as, is used to eliminate offset by bringing the process variable back to its set point. Without integral action proportional control will always be away from the set point.

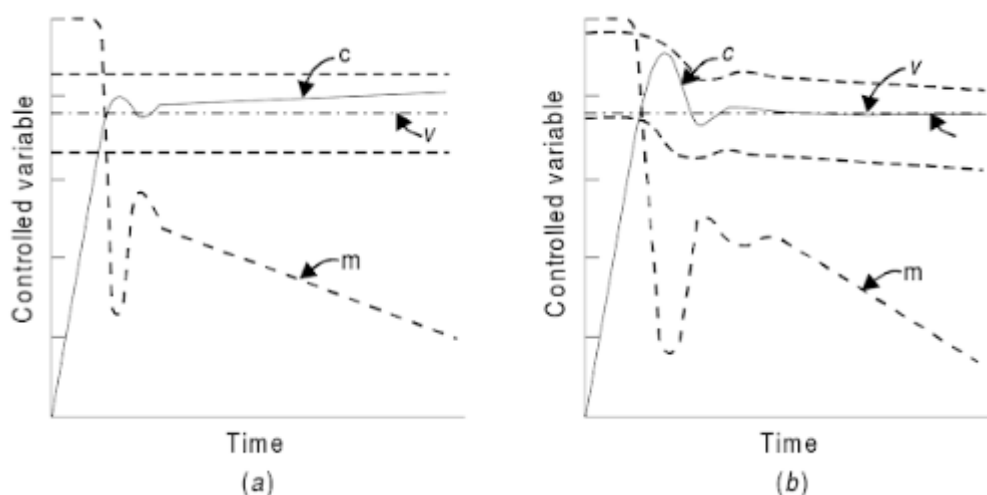


Figure 51 - Proportional and Integral Control

Proportional and integral control of a temperature controller is shown in figure 51. Proportional control in figure 51 is shown as diagram (a) and proportional and integral action is shown as diagram (b). In diagram (b) the offset of the temperature is almost discharged and the temperature is kept close to the set point labelled as 'v'. The initial overshoot of the 2 term control (diagram b) is a lot larger compared to the proportional control only diagram (a). The greater overshoot is created due to the action of the integral response. As the temperature is initially climbing it is well below its set point so the proportional gain is high trying get the temperature to set point

The mathematical equation for proportional and integral control is shown below.

$$m = K_c \left[e + \frac{1}{T_i} \int e dt \right] + b$$

Equation 3 - Proportional and Integral Control.

- “Ti” is what represents integral time from the controller.

By introducing integral action to eliminate offset the process variable would be able to reach its desired set point. Integral action works by integrating the area under the error curve which results in no offset.

4.5.6 – Proportional, Integral and Derivative Control

The most widely popular control technique is the 3 term or PID control [49]. With proportional, integral and derivative action all combined extremely fine tuning of control loops can be achieved. Whilst “proportional action looks at the current process whilst the integral action looks at the previous error values. Derivative action looks to predict the future error values” [42]. The derivative action examines and attempts to compensate for the current rate of change in the previous and current error values.

The mathematical operation for proportional, integral and derivative controller is shown below.

$$m = K_c \left[e + \frac{1}{T} \int e dt + T_d \frac{d}{dt} e \right] + b$$

Equation 4 - PID Control

- “Td” represents the derivative time for the controller.

When stability is an issue derivative control is recommended and often corrects the problem. The derivative part of the controller anticipates the future process of the errors, the controllers output would the change proportionally to the rate of change of the errors. The rate of change of the errors would then be multiplied by the derivative constant resulting in increased system response and a much less initial overshoot.

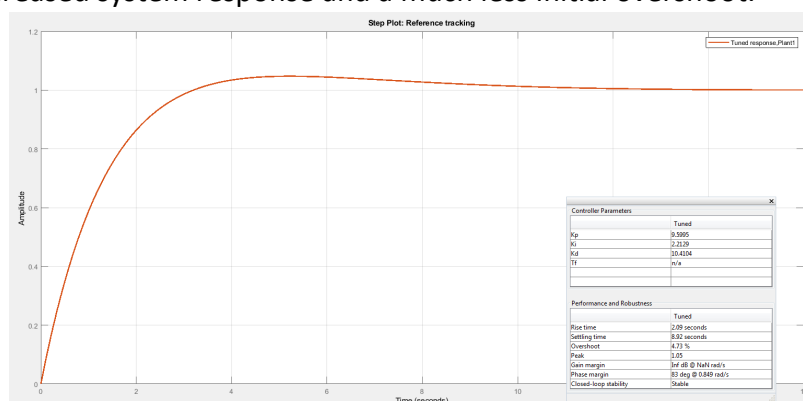


Figure 52 - PID Control Curve

As shown in figure 52 which is an example of a three term control curve taken from a previous PLC assignment created by the author.

- The proportional gain smooth's out the process making the result have an offset either below or above its set point.
- The integral action eliminates the offset so the process variable remains steady on its set point but creates a slightly initial big overshoot.
- The derivative action predicts future errors resulting in no or a very little overshoot.
- Combine all 3 control actions together and the perfect control curve is created as displayed in figure 52.

Chapter 5 – Design and Implementation

5.1 – Project Requirements

The project is to simulate a central heating system by designing software and hardware that would control the amount of water flowing through the copper coils releasing heat into the wooden box. The temperature probe located within the insulated wooden house which is a RTD PT100 would then provide a feedback signal to the PLC where a 0 – 20mA signal is send to the positioner of valve so then the valve can be controlled using three term control PID.

The requirements are as follows.

- To create a HMI design to display exactly what the process does and where the warnings and alarms are kept.
- For a control valve to control how much water should pass through the coils.
- To have a tank and box temperature shown on the HMI displaying accurate readings.
- Warnings and alarms to be derived when the temperature exceeds its set point values.
- An immersion heater to keep the vessel at 60°C.

5.1.1 – Software PLC Ladder Logic Design

When designing the PLC program an I/O list is important to make because it clearly displays the inputs and outputs needed. This would then help decide what PLC to use making sure that the PLC could handle all the connections. Listed below is how the operation of the project should run.

- All warning and alarms healthy.
- Operator inputs a room temperature setpoint into the HMI.
- Operator starts program.
- If the room temperature was to climb over its alarm setpoints the process would stop causing the process to enter a tripped condition.
- The immersion heater is to control between the tank low and high warning setpoints.
- When trip activated pump, immersion heater and control valve would stop.
- If the tank level was to go lower than the immersion heater the level switch would cause the process to stop and enter a tripped condition.
- When either a warning or alarm become active a green LED would turn to red to warn the operator.

5.1.2 – Project Design Block Diagram

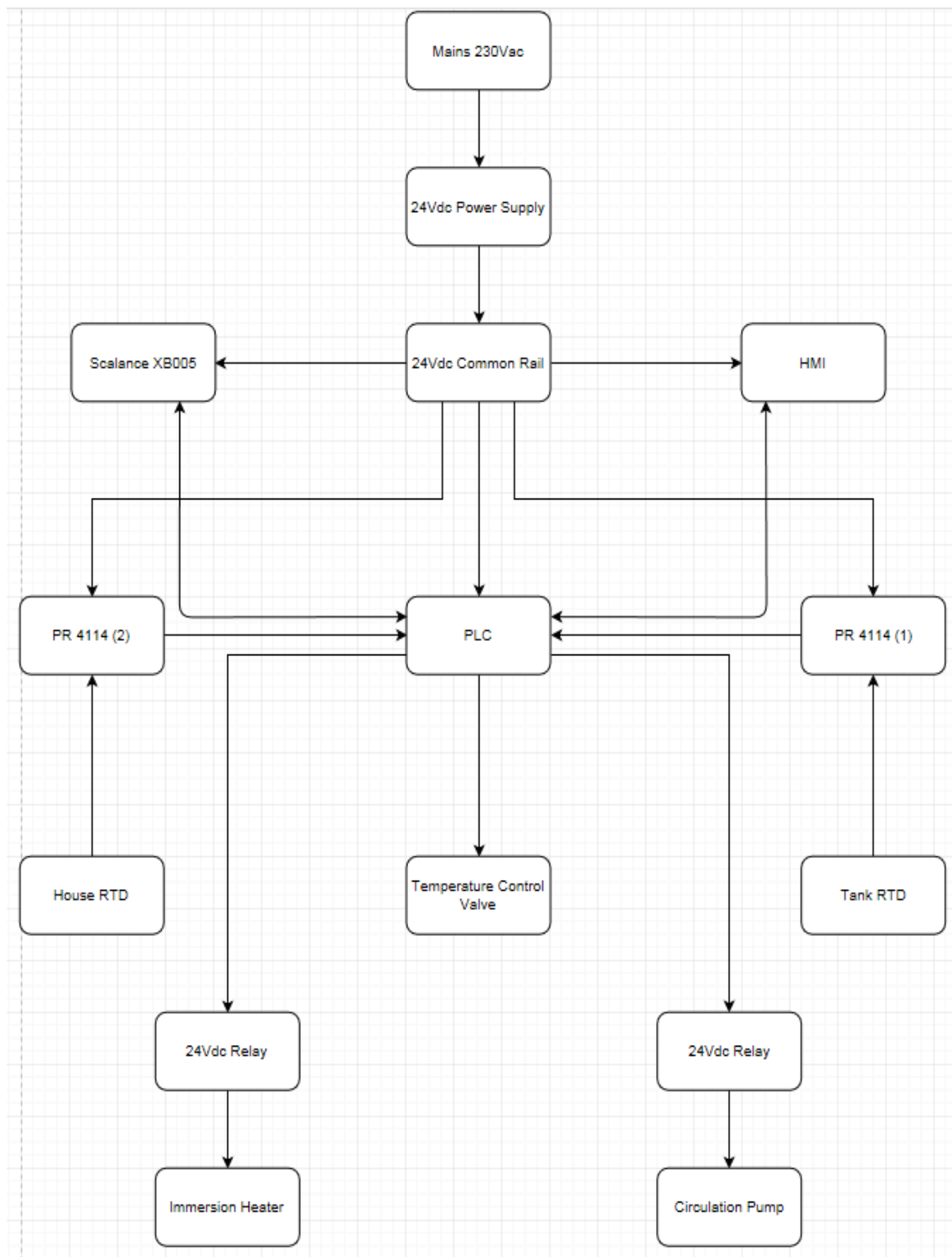


Figure 53 - Project Block Diagram

5.1.3 – Prototype Control Circuit Panel

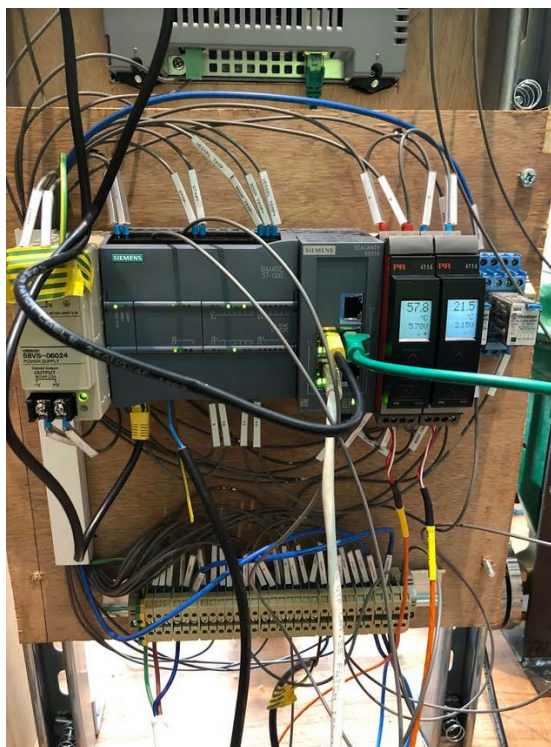


Figure 54 - Constructed Control Panel

Figure 54 is what has been created by the author for this project to work successfully. The rail at the bottom with all the terminals on it is where each input and output would be terminated.

See appendix for loop drawings for the control board.

5.1.4 – Prototype Design

The project prototype is shown below as well as a simple operation description.

- PLC controls water vessel temperature by switching an immersion heater on/off.
- The circulating pump pumps the water through the control valve or through the bypass if the control valve is fully shut. This stops the pump from dead ending.
- Inside the wooden box is a temperature transmitter that controls how much hot water travels the copper coils via a control valve. The control valve is controlled by a PLC using three term control.
- Exiting the copper coils it travels through a non-return valve then back to the water vessel where the process is repeated. Copper coils are shown in figure 56.
- The HMI is where the house temperature set point can be entered. Also the gain, integral or derivative values can be changed through the HMI.



Figure 55 - Prototype Build



Figure 56 - Copper Coils used for heating the Room.



Figure 57 - Prototype Build

5.1.5 – Prototype Build Cost

Item Description	QTY	Each (£)
Following items gathered from BOC Gases Stores		
PR Units 4114	x2	158.71
PT100 RTD 3 wire	x2	38.14
Fisher Fieldvue Positioner	x1	909.5
Fisher Plug & Seat Valve	x1	0.00 (From Scrap)
Omron 24V Power Supply	x1	181.1
Finder Relays	x2	9.55
0.75mm Cable	50meters	87
22mm Copper Pipe	20meters	50.12
1/4 Inch Copper Pipe	20meters	22.55
200Litre Water Tank	x1	18.6
3mm Thin Plye Wood Sheet	x1	40.6
	TOTAL	£1,722.27
Following items supplied by UWTSD		
S7-1200 CPU1214C DC/DC/DC	x1	288.88
Siemens HMI KTP700 Basic	x1	600
S7-1200 Scalance XB005	x1	111.39
SB 1232 AQ1 x 12bit	x1	86.9
	TOTAL	£1,087.17
TOTAL PROJECT COST £2809.44 ±5%		

See Appendix for all data sheets for the chosen hardware.

5.1.6 – HMI Root Screen

The root screen is the main screen which is first displayed when the HMI is powered up. The main function of the root screen have been shown around figure 58. The 3 LED's "Warning Active", "Alarm Active" and "System Active" are green when healthy and red when in a tripped condition. These are to help identify the fault if the process stops. The 3 buttons on the top tagged "Operation", "Warnings & Alarms" and "Default Values" when pressed instantly direct the user to that screen.

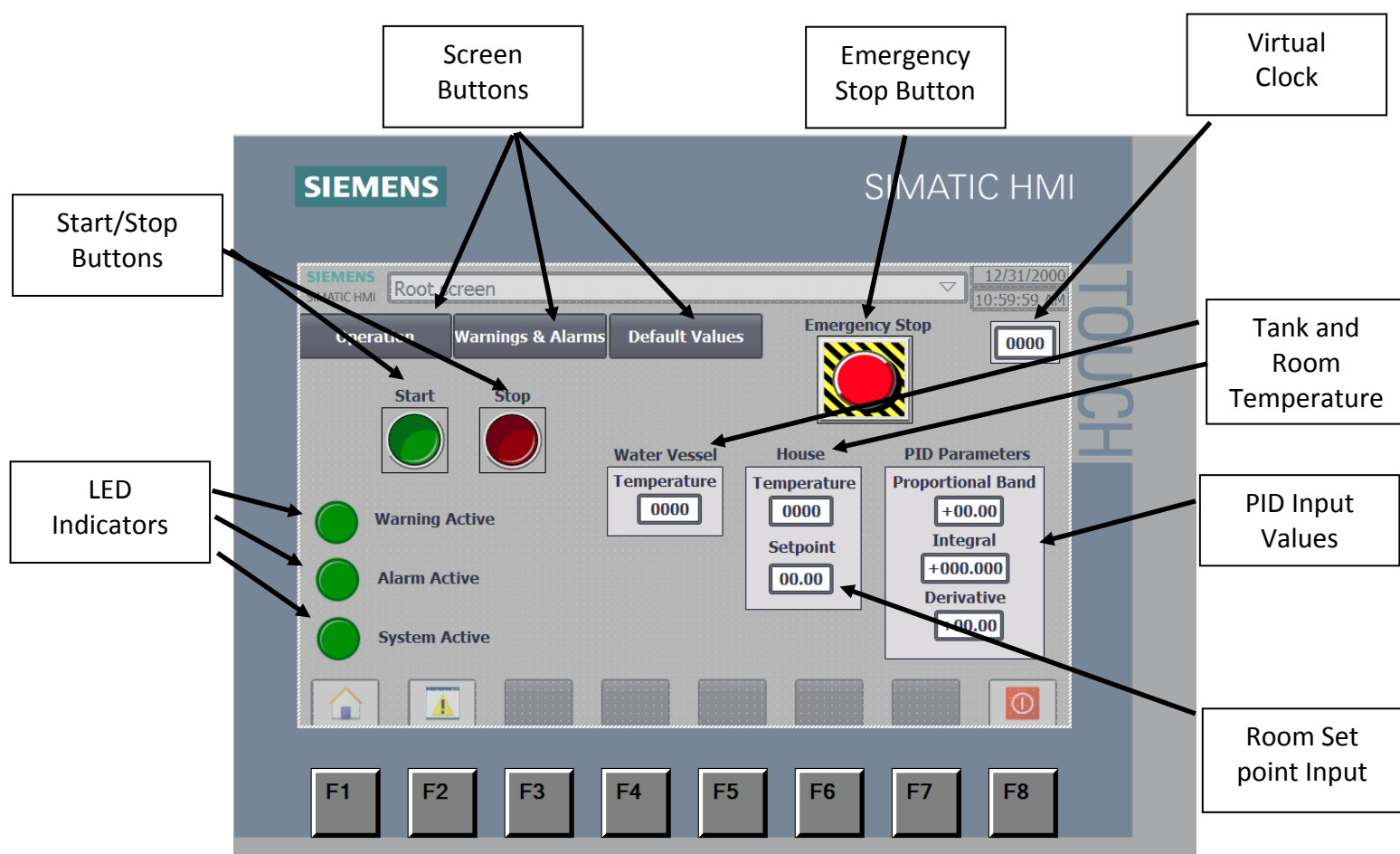


Figure 58 - Root Screen HMI

- Both room temperature and vessel temperature are displayed on the root screen as well as a house temperature set point input box. This is where a room temperature set point can be entered for the PLC to control to.
- When tuning the control valve for its purpose the PID constant values can be changed so that the correct tuning of the valve can be achieved.
- The process can be started or stopped from either the HMI screen or the physical buttons mounted either side of the HMI.
- The virtual clock was placed so the operator knows that the HMI is connected to the PLC.

5.1.7 – HMI Warnings & Alarms Screen

The warnings and alarms screen is for clearly identifying what part of the process caused a warning or an alarm to occur. A warning signal is to alert the operator that the process is getting close to an alarm resulting in a shutdown state. Each green LED is allocated to specific value which is specified in the default value screen or in the network 5.

The 2 unmarked green LED's furthest right of the screen are to just identify an alarm or warning has be activated.

The larger LED's labelled "PID Alarm" and "Low Water Level" are enlarged because they are the most critical part of the process. If the water level in the water tank started to fall below the immersion heater it could risk of burning the hard plastic resulting in a fire.

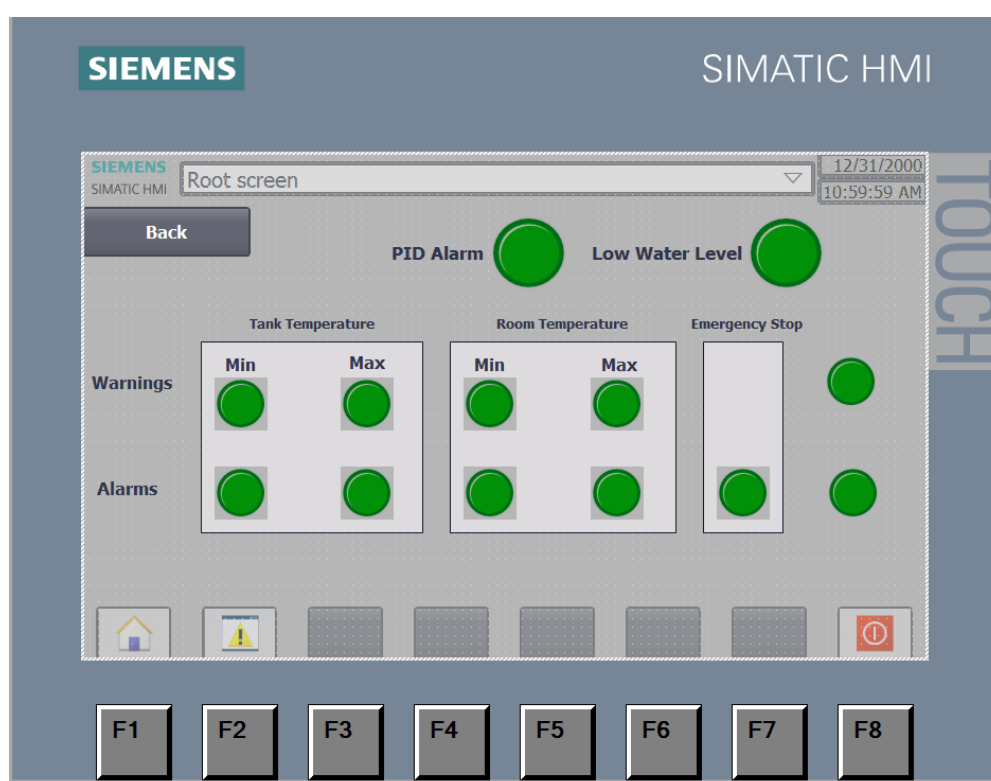


Figure 59 - Warnings & Alarms Screen HMI

Both the tank temperature and room temperature have a minimum and maximum value for warnings and alarms.

5.1.8 – HMI Default Values Screen

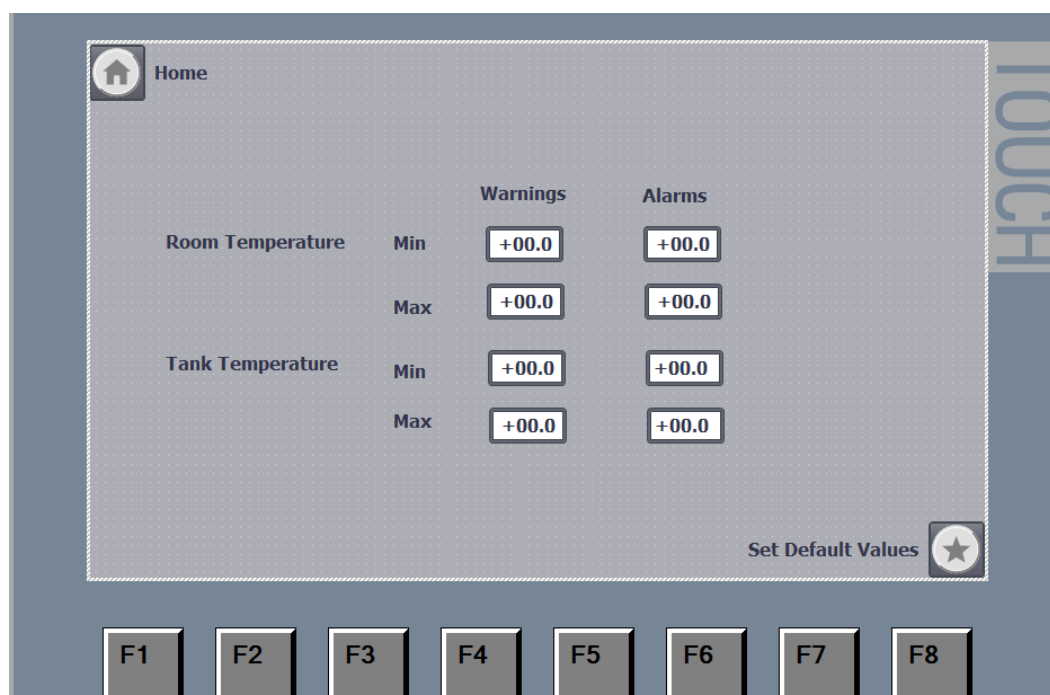


Figure 60 - Default Values Screen HMI

This screen is very basic. Here each warning and alarm value for both the room and tank temperature can be changed to what the operator would like. As discussed on the previous page each of these values correspond to a green LED on the warnings and alarms screen.

In the bottom right hand corner is a button which says “Set Default Values”. A scenario could be that an operator has been playing with this project and has decided to change the values of the warnings and alarms to possibly increase the temperature of the room. Another day a different operator has decided to play with this project but it has all the settings from the previous operator installed. By pressing the “Set Default Values” buttons it automatically sets the values to a desired value which is pre-installed into the PLC.

The top left button which says “Home” when pressed quickly diverts the user back to the home screen.

5.1.9 – HMI Operation Screen

The operation screen displays the exact operation of the project clearly showing the stages of operation. With the both temperatures displayed as well it would show the user if the room was ever reaching the desired set point. A lot of the animations such as the water vessel, immersion heater, pump, control valve, copper coils and temperature transmitter where found within the global libraries of TIA 13 programme software. When the process is online the pump should be coloured red when it's not running and coloured green when it is running.

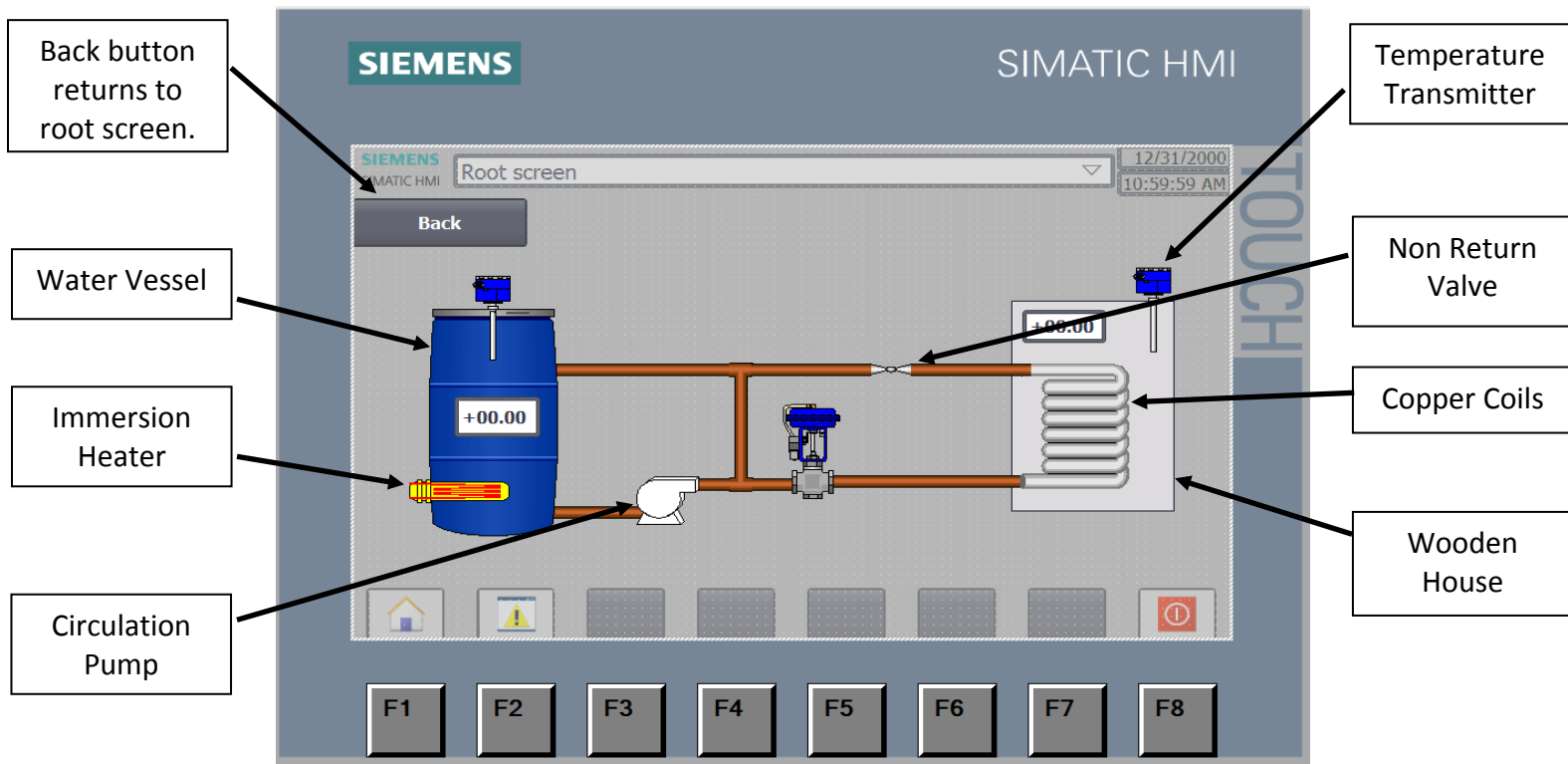


Figure 61 - Operation Screen HMI

5.2 – PLC Network Program

5.2.1 – Network 1

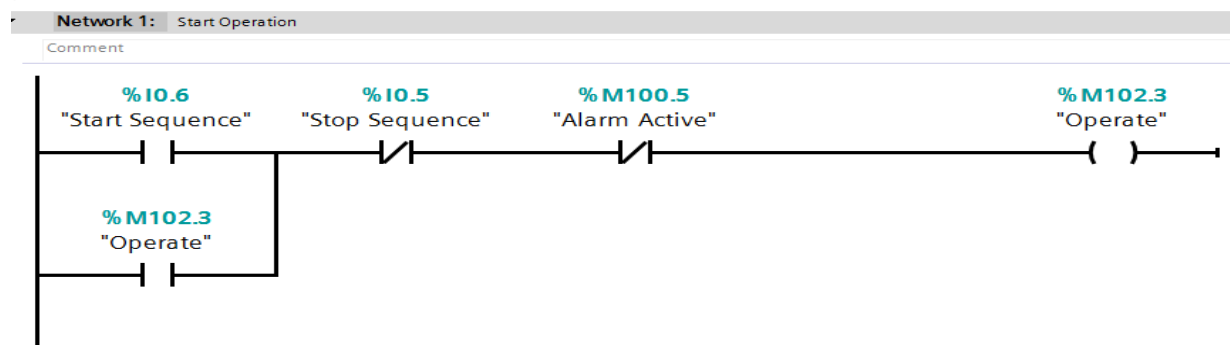


Figure 62 - Start and Stop Latching Sequence

Network 1 is the start and stop circuit which are fired by 2 switches mounted either side of the HMI. If the 'Alarm Active' tag is healthy the internal contact 'Operate' would be called in and therefore should latch the circuit on.

5.2.2 – Network 2

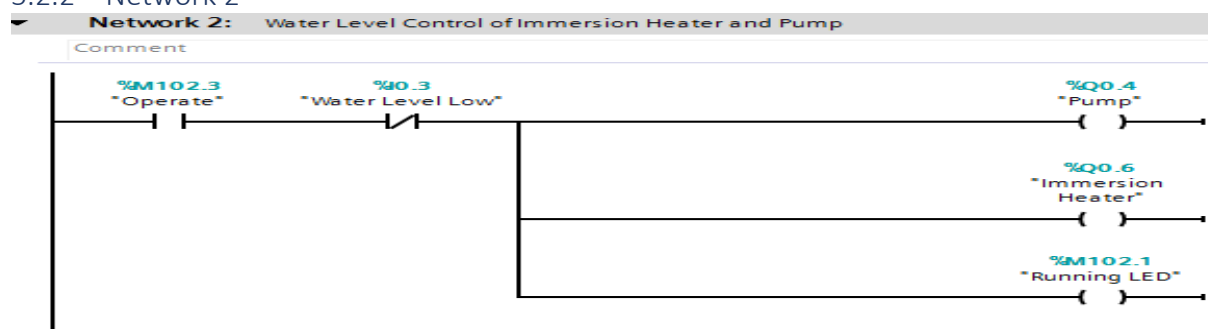


Figure 63 - Operation Circuit

Network 2 displays how once the process is started the immersion heater and circulation pump come on. Once on a running LED remains on saying the system is active.

5.2.3 – Network 3

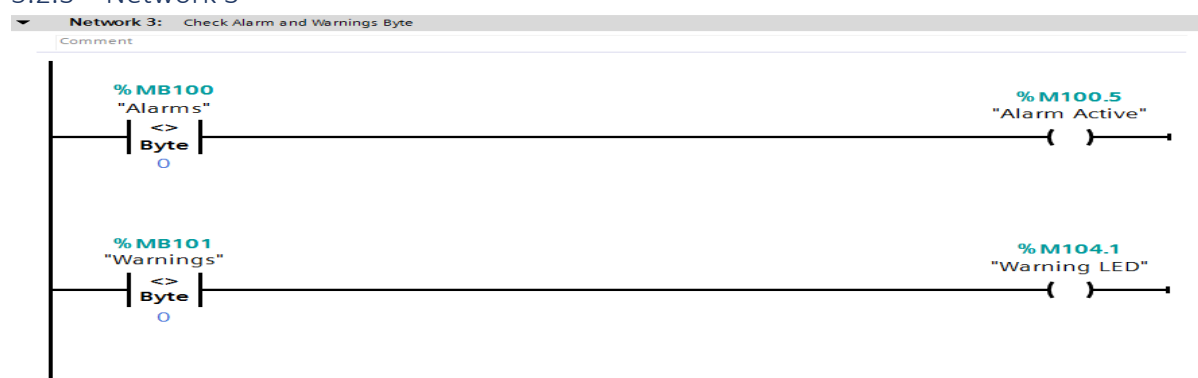


Figure 64 - Generation of Alarm Active and Warning LED

%MB100 and %MB101 are both 'bytes'. Either one of its 'bits' equate to 1 it brings in either a warning or an alarm. The alarm or warning is then displayed on the HMI.

5.2.4 – Network 4

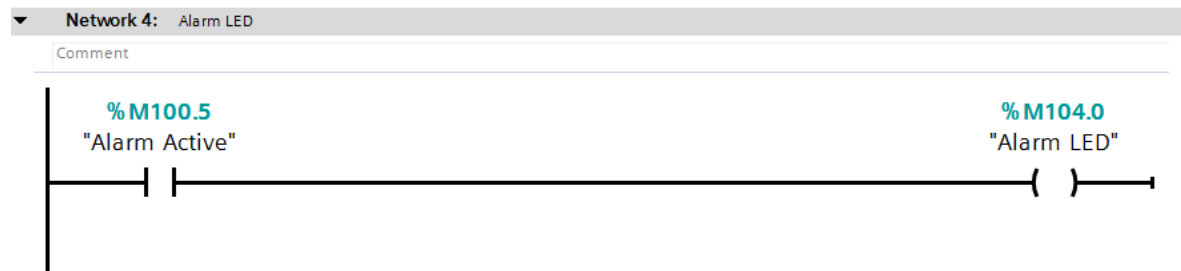


Figure 65 - Generation of Alarm LED

5.2.5 – Network 5

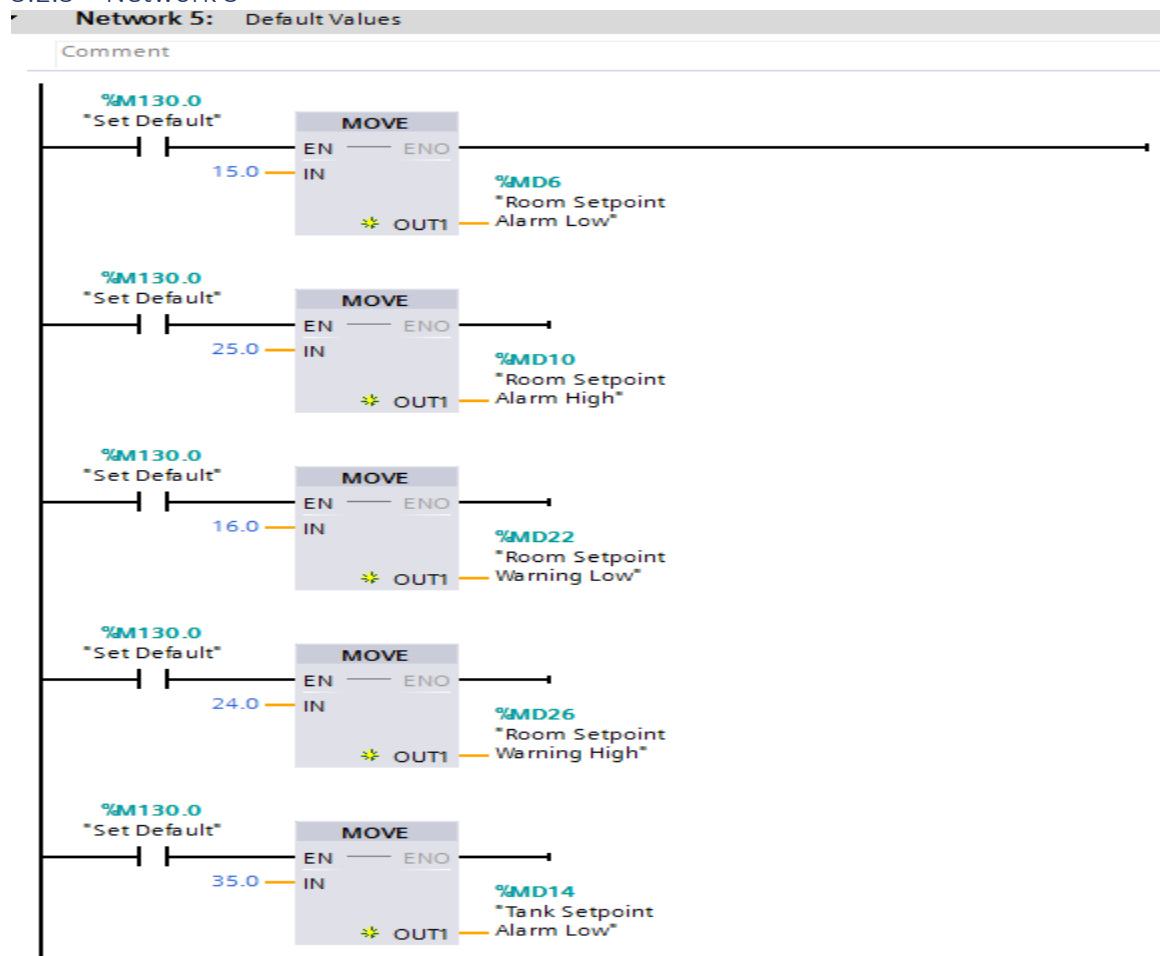


Figure 66 - How the Default Values are set

Figure 66 shows how each value in the 'Set Default Values Screen' gets their default value. When the MOVE block is made once the set default button is pressed each value it set to the value which is displayed on the 'IN' of each move block. The rest of Network 5 is displayed in the file containing all the computer software.

5.2.6 – Network 6

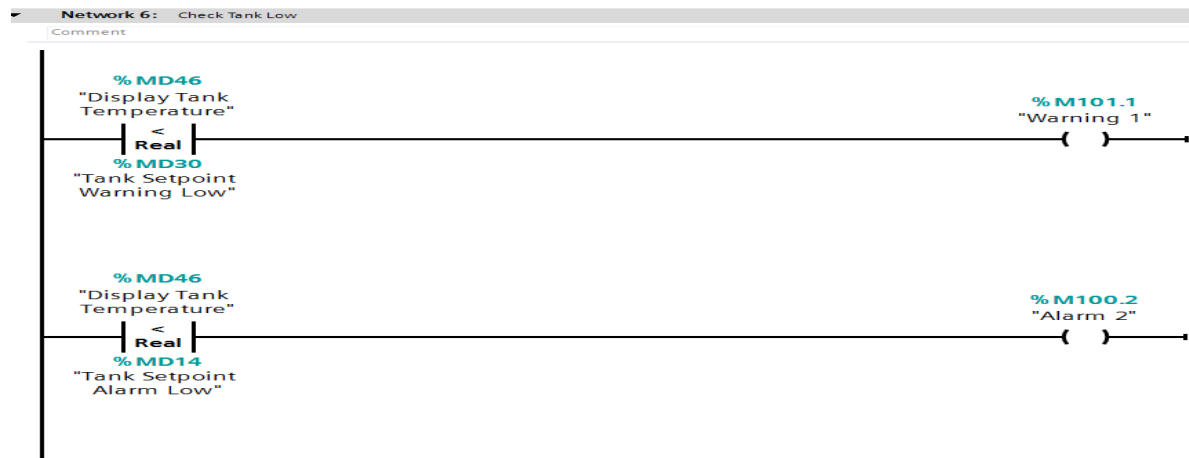


Figure 67 - Low Tank Temperature Alarms and Warnings

5.2.7 – Network 7

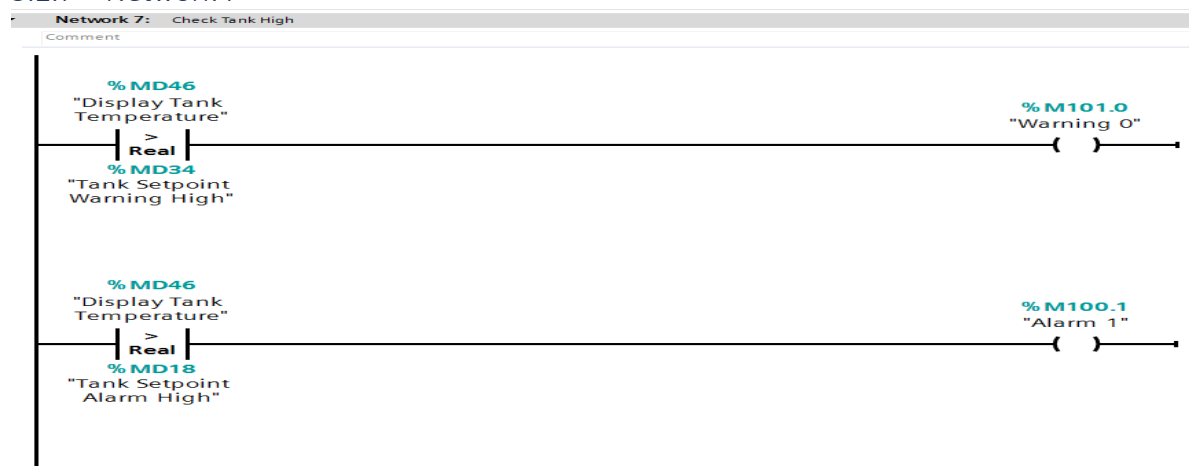


Figure 68 - High Tank Temperature Alarms and Warnings

5.2.8 – Network 8

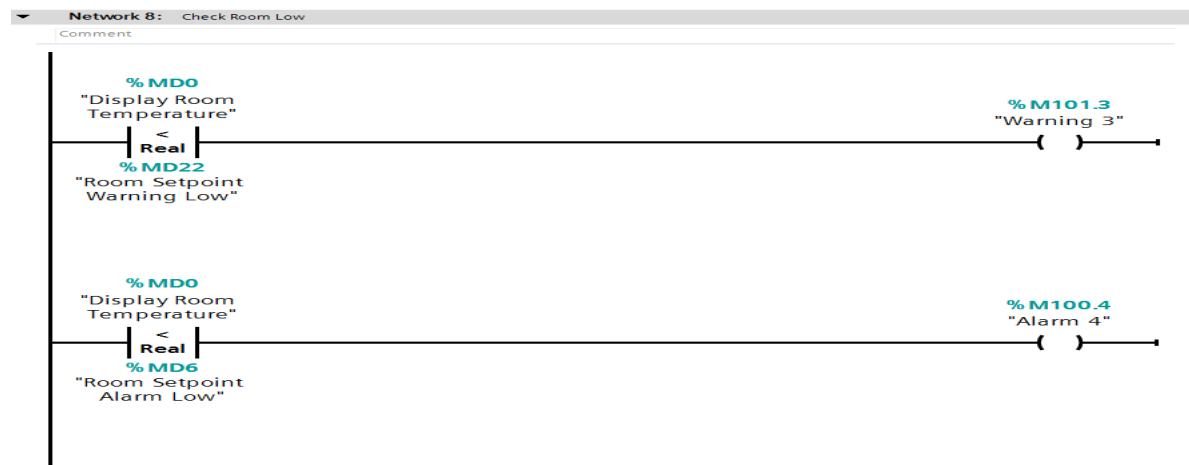


Figure 69 - Low Room Temperature Alarms and Warnings

5.2.9 – Network 9

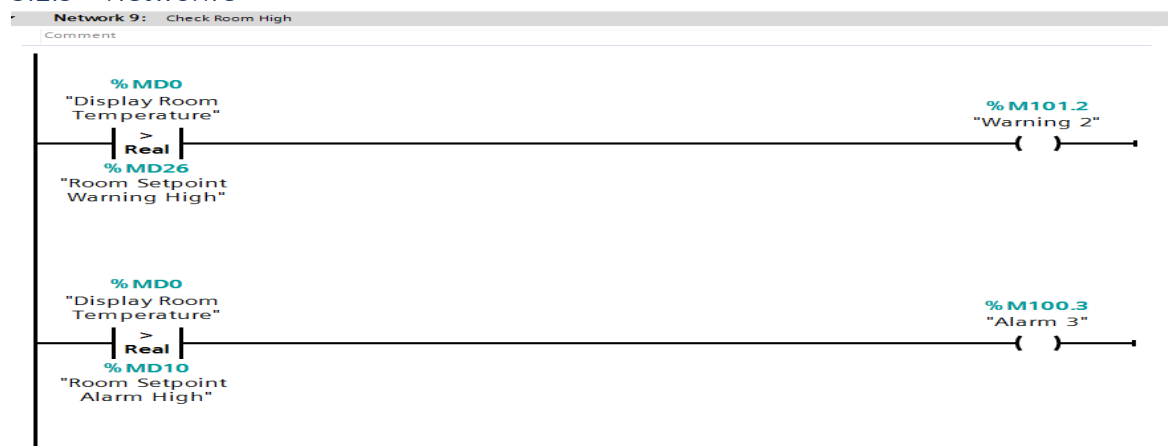


Figure 70 - High Room Temperature Alarms and Warnings

Figures 67, 68, 69 and 70 are all how the warnings and alarms are generated for the vessel and room temperatures. For example in figure 70, the displayed room temperature is the real value which is being displayed on the HMI. If that value was to exceed either the high room set point warning or alarm value the correct warning or alarm LED would become active.

5.2.10 – Network 10

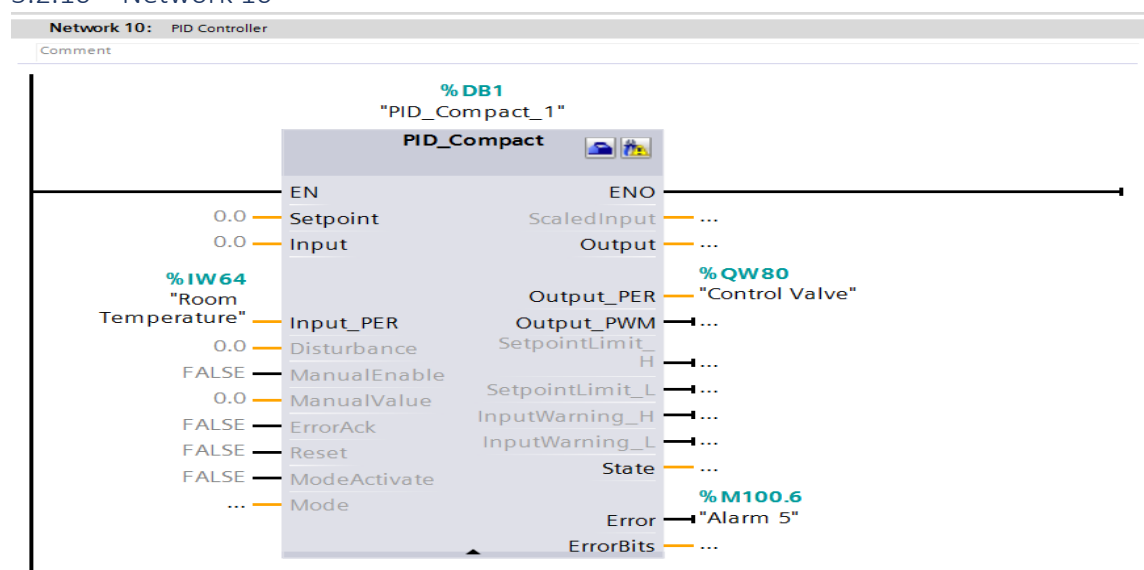


Figure 71 - PID Block for Control Valve

%DB1 is the PID Compact block which operates the control valve to allow the hot water through the copper coils. On the root screen the PID constants can be entered to alter the tuning of the PID compact block. The output which is %QW80 is set to 4 -20mA which would control valve. The output all depends on the input which is %IW64. The output is a linear signal. If a fault occurs with the PID block an error is sent out which brings in Alarm 5.

5.2.11 – Network 11

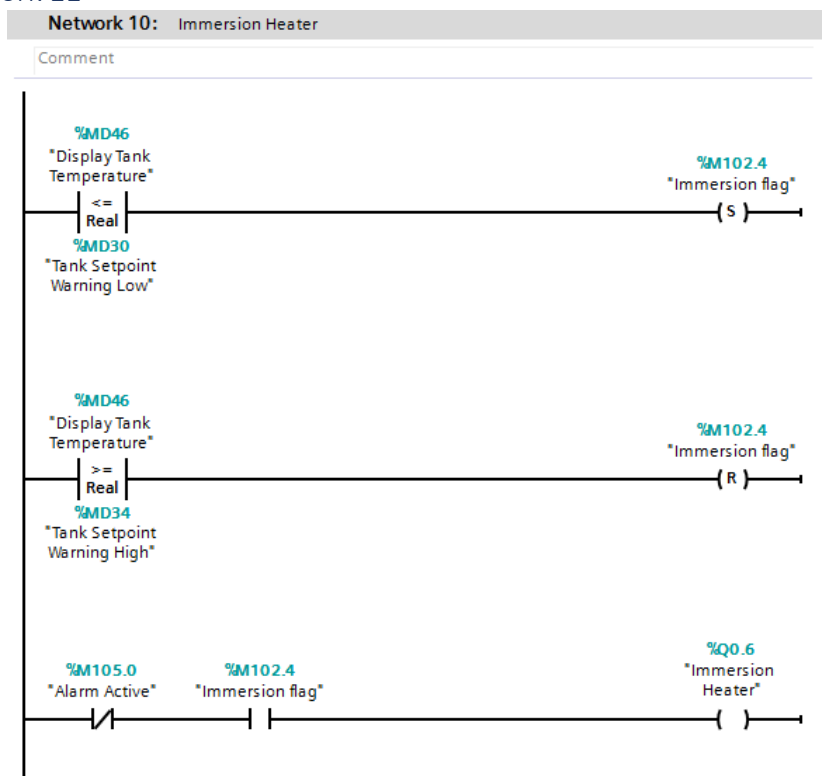


Figure 72 - Immersion Heater Control

The temperature of the water vessel is controlled by using a less than or equal to and a greater than or equal to comparator. The immersion heater is controlled by the low and high warning set points. If the tank temperature goes below the tank warning set point it energises the 'Set Bit' function of the immersion flag tag. When the 'Setbit' function is equal to 1 the immersion heater is on. The 'immersion flag' tag is a 'bool' data type meaning that it is either on or off (1 or 0). With the 'Alarm Active' set before the 'Immersion flag' any alarm was to become active it would switch the immersion heater off. Without the 'Alarm Active' the immersion heater would just control between the set points.

5.2.12 – Network 12

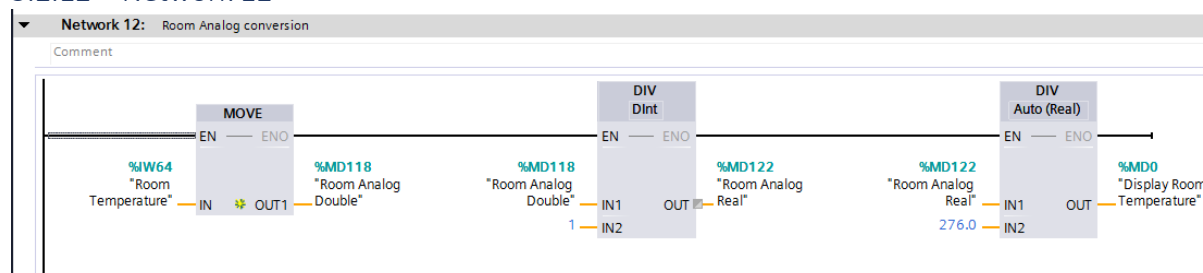


Figure 73 - Converting Raw Analogue Signal to Display Room Temperature

5.2.13 – Network 13

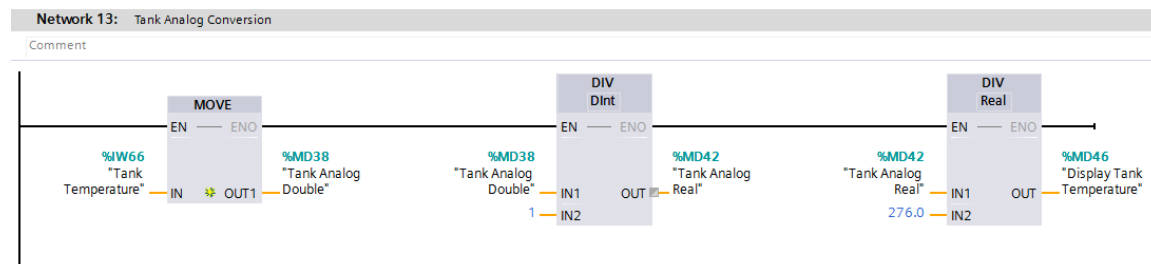


Figure 74 - Converting Raw Analogue Signal to Display Tank Temperature

Both network 12 and 13 convert the raw “analogue in” value which is a “word” data type which then moved to an analogue double and divided by 1 to convert it to a “Real” data type which is then divided by 276 to show an accurate temperature reading ranged from 0 to 100. Figure 79 shows the how to convert from hexadecimal to decimal.

5.2.14 – Network 14

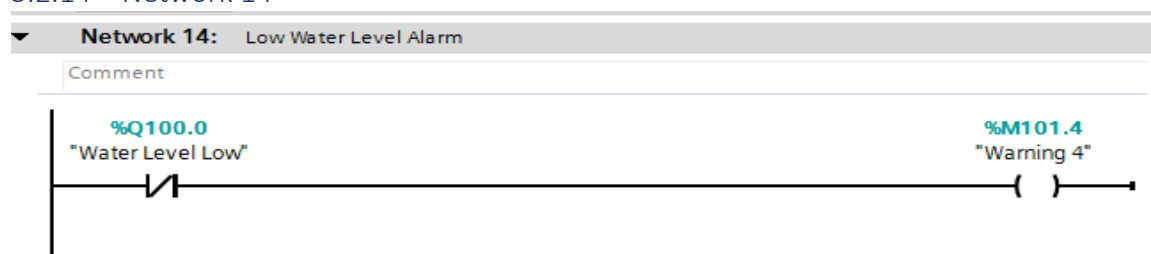


Figure 75 - Water Level Alarm Generation

5.3 – Program Alarm Operation Block Diagram

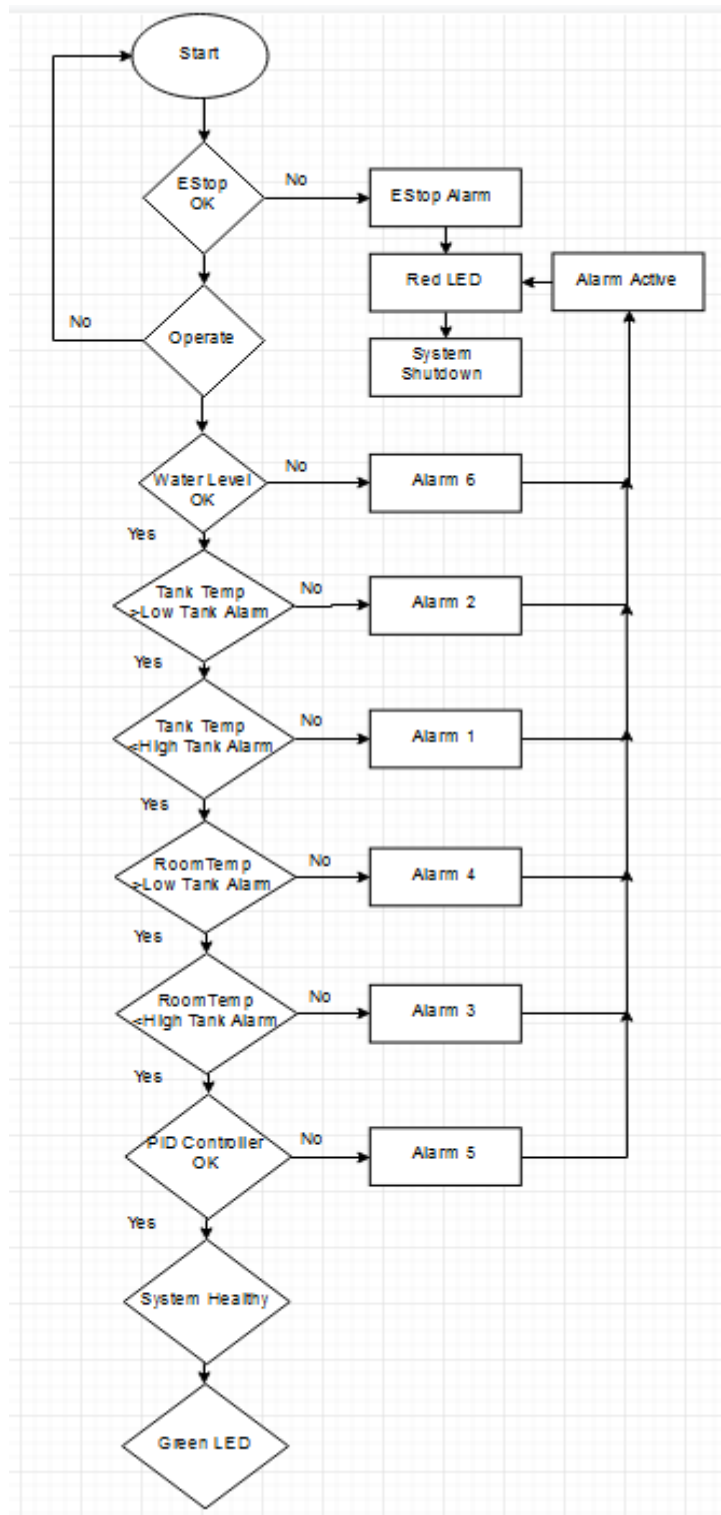


Figure 76 - Alarm Generation Block Diagram

Chapter 6 – Analysis

6.1 – Test 1

To carry out a form of testing for this project what was decided to do, was to see the effective on the house temperature when the control valve was opened in manual steps with the water tank temperature controlled at greater set points.

For this test the wooden house was insulated with Rockwool to help maintain the heat within the box. Rockwool was chosen due to it having many advantages as an insulating material as listed below.

- Can withstand up to 1000°C without melting.
- The material allows moisture to exit therefore allowing the Rockwool to being able to breath.
- If dual density slabs are used which are 120mm thick the structure or building has the potential for the u value to reach 0.3 keeping the structure warm for longer.. This would lower energy bills [50].

Even though heat raises 2 small 12V fans were fitted underneath the copper coil inside the wooden house to help blow the heat out and to aid cooling. These fans were powered by a rechargeable lead acid battery which had 7AH worth of energy.

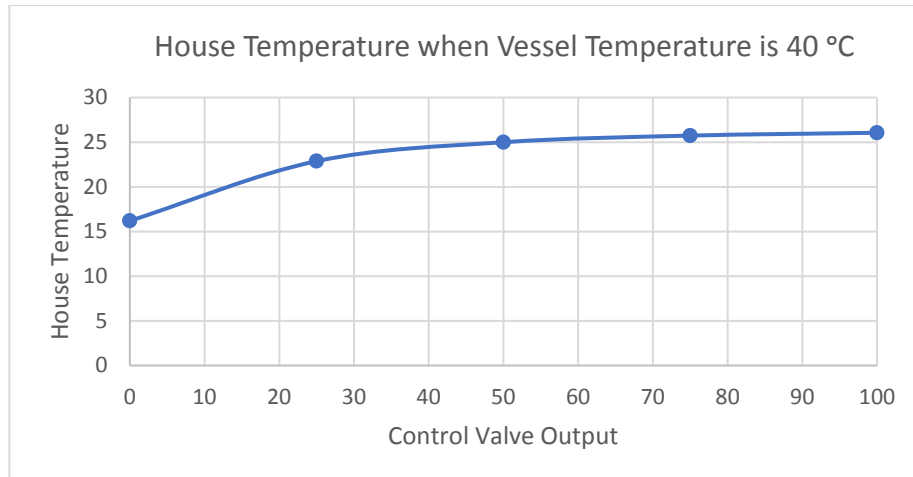


Figure 77 - 12V Fans

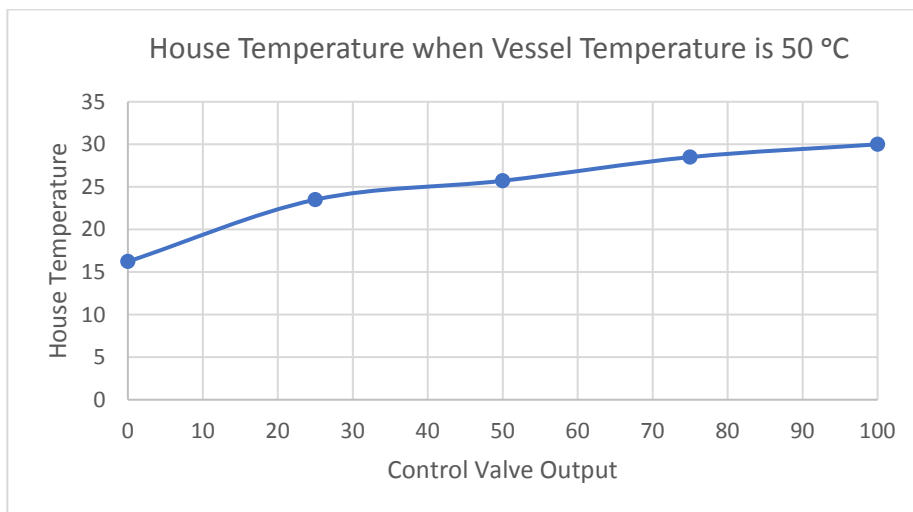


Figure 78 - 12V Battery Lead Acid 7AH

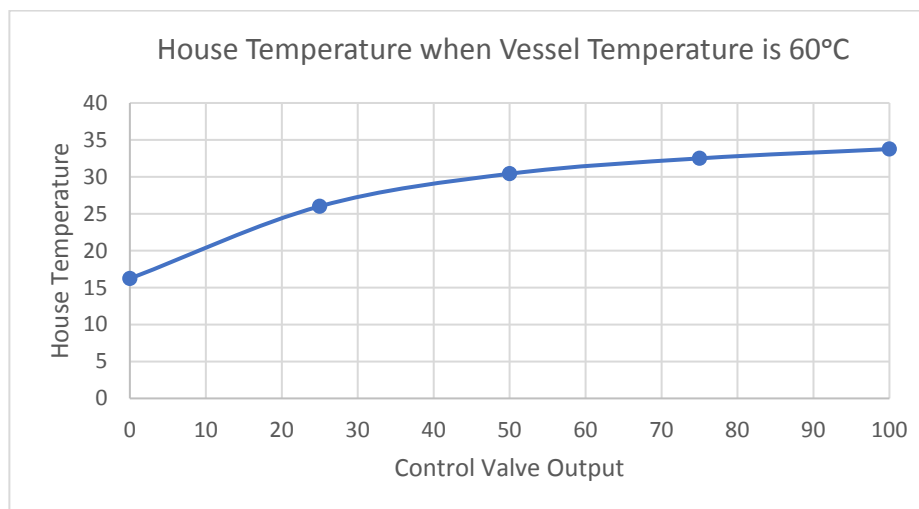
Three experiments were carried out with the vessel temperature set to 40°C, 50°C and 60°C. The control valve was then opened from 0% to 100% in 25% step changes allowing larger flows of hot water to pass through the coils. The data recorded was the room temperature when the reading had settled out.



Graph 1 - House Temp Effect When Vessel is 40°C



Graph 2 – House Temp Effect When Vessel is 50°C



Graph 3 - House Temp Effect When Vessel is 60°C

To make the results a fair test the manual bypass valve was fully shut throughout so that the same amount of hot water could be bumped through the coils at the same output signal. As shown by graphs 1, 2, 3 each graph delivers a positive correlation of results as expected. Clearly the hotter the vessel temperature the hotter the house temperature gets. To increase the efficiency and to gain greater temperature within the house heat saving techniques need to be added. As it expected to achieve greater temperatures and to have a more linear curve, the vessel temperature needs to be 60°C.

By lagging the copper pipes exiting and entering the vessel this would save the heat escaping resulting in more heat being able to enter the house. Lagging the pipes with Rockwool insulation would trap the heat, this would also keep the water in the vessel hotter resulting in the need of the immersion heater to be called in less often. This would save on energy bills also.

Performing a test on the rate at which the house cools down once it reaches its maximum temperature would show how efficient the house insulation is at keeping the heat trapped inside the house from the copper coils.

6.2 – Test 2

The second test that was performed was to match the input value to read the same as the value on the HMI. As shown below the raw input value entering the MOVE block which is labelled as IW64 is reading 16#1732. This strange number is in hex decimal which when converted to a decimal figure reads 22.

The authors workings out are shown below.

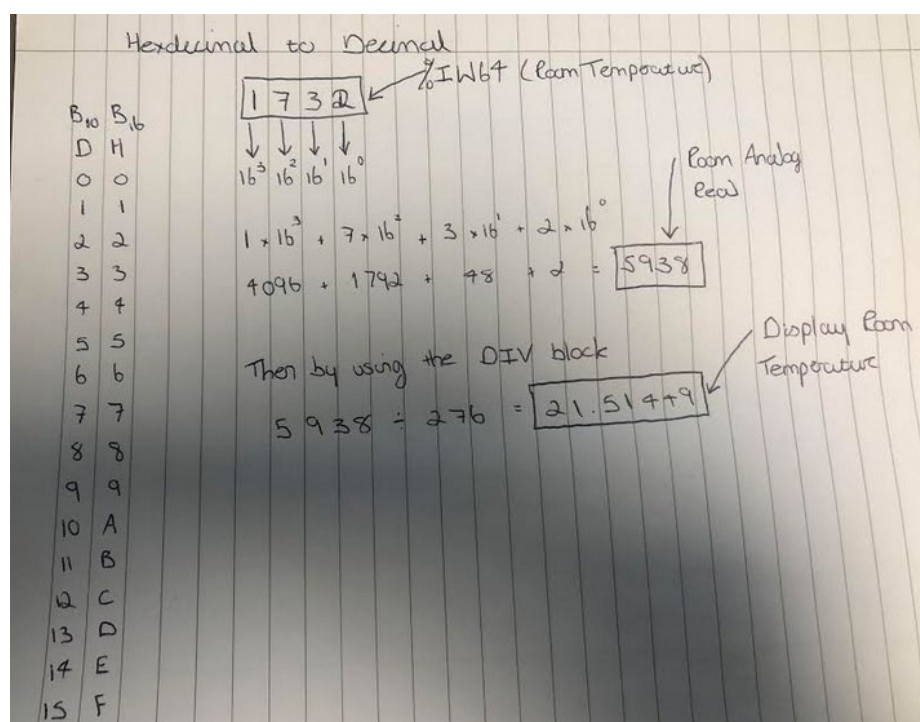


Figure 79 - How to Convert Hexdecimal to Decimal

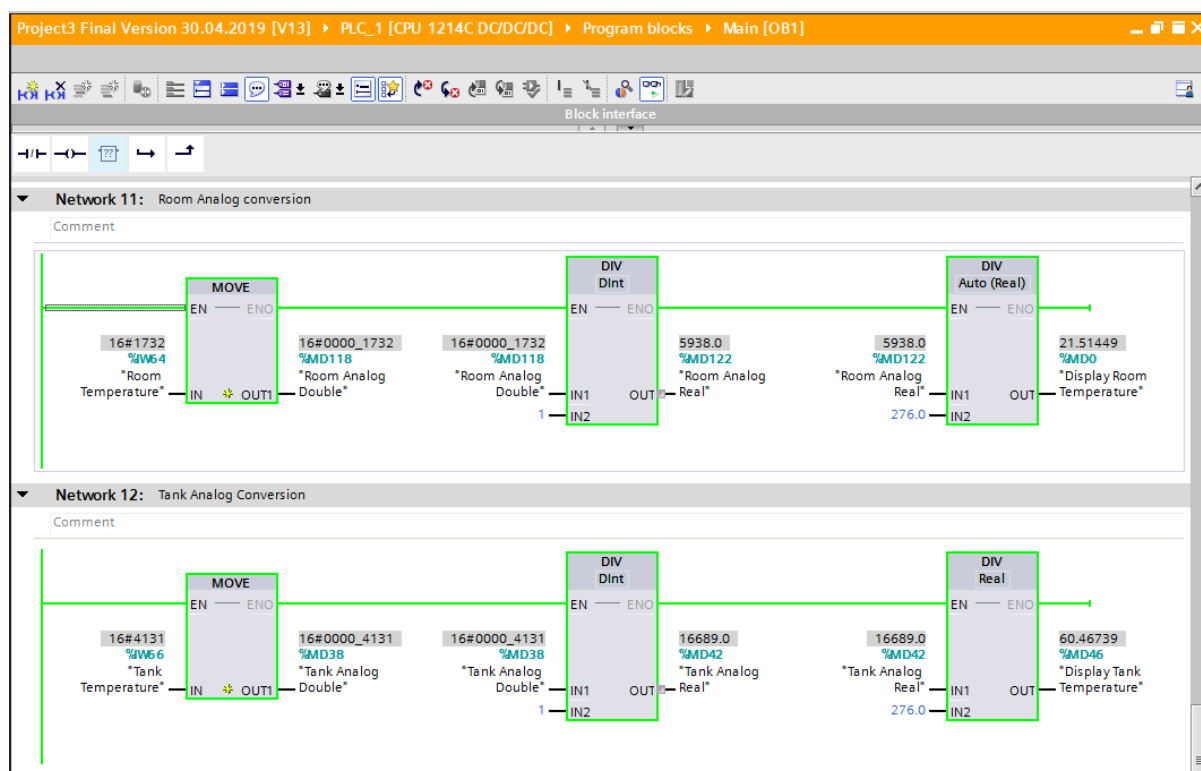


Figure 80 - TIA3 Online Diagnostics

With figure 80 supporting the values shown in figure 79 the values must be correct. To support the experiment further a digital thermometer was then placed inside the wooden house to confirm the temperature was 22 degrees which it was.

TIA 13 has a useful function which allows the user to go online to the PLC to see what

exactly the program is doing. Shown by figure 76 by pressing  all green lines of ladder would appear. The green lines of ladder state that the ladder is ok and functioning. If the lines of ladder were in an unhealthy state instead of being green they would be dotted blue.

To get the correct division factor value which enters IN2 on the last block took a lot of trial and error. With the starting figure being 3208 the actual tank temperature on the HMI was a lot lower than expected. So by lowering the division value the tank temperature was slowly increasing. Once the temperature on screen matched the digital thermometer the division value was correct.

Online mode is a great way to see exactly what's going on within program and aids fault finding massively.

6.3 – Test 3

With the rest of the loops commissioned the last and hardest loop was to get the 'PID Compact' block from the PLC to control the temperature in the house to whatever suitable set point was entered via the root screen. Figure 81 describes the basic configuration settings of the PID Compact block. As shown the loop is for temperature and requires an analogue signal in and an analogue signal out.

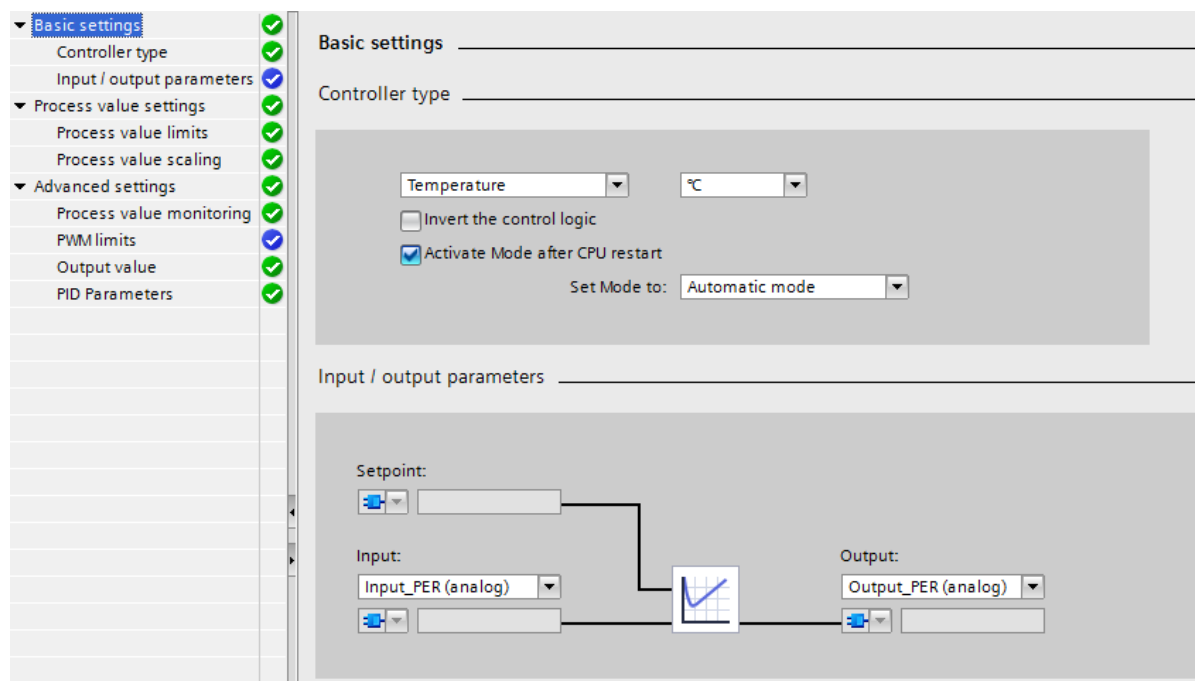


Figure 81 - Configuration of Basic Settings

Whilst speaking to the support engineer from Siemens he said that if all the ticks on the left aren't green the PID block won't work. The process value setting is here the high and low limits for loops input signal are set, this project being 0 to 100.

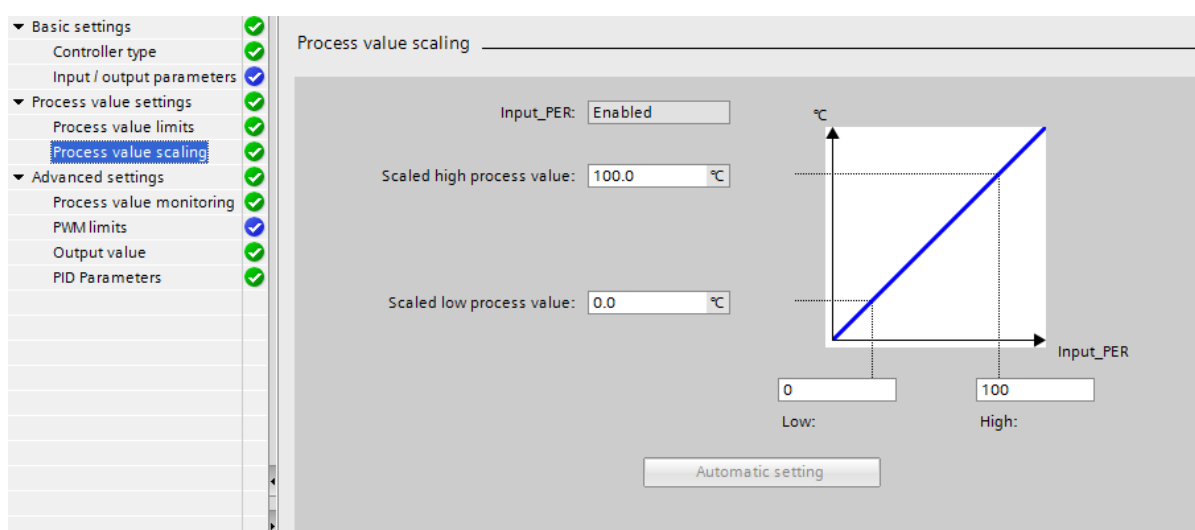


Figure 82 - Configuration of Process Scaling

Once the configuration of the PID block was complete, next was to commission the loop. Here the input value, set point and output can be witnessed using a live trend showing the user exactly what is happening. Below on figure 84 when the set point was lowered so did the output.

Due to this being a cold start the house temperature was already low to begin with. So as the set point was decreased the valve output went with it. The gain value was then increased from 1 to 3 which slowly ramped the valve open until it settled at 18.35MA

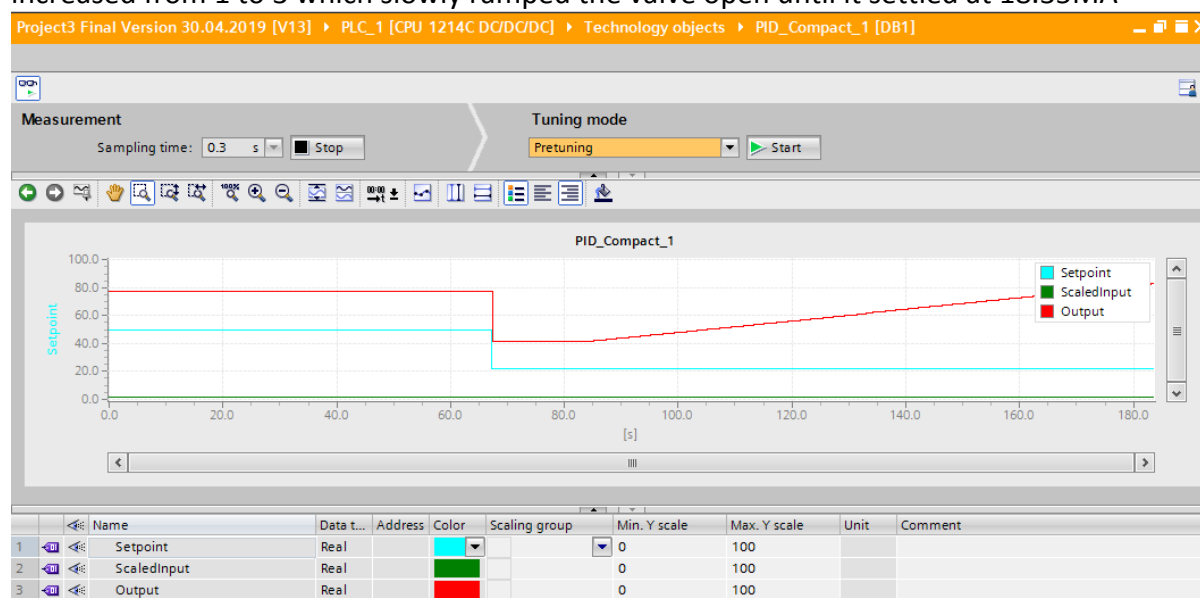


Figure 83 - PID Compact Commissioning Screen



Figure 84 - PID Compact Commissioning Screen

With the valve tuned and set up, throughout the tests the temperature never managed to reach its set point, even with a vessel temperature of 65 degrees. The process variable would be below its set point resulting in the valve output to go fully open, the trouble was

the time taken get up to the desired temperature just took too long. When the temperature finally managed to reach within distance of the set point the valve would just remain fixed open at that position.

Chapter 7 – Evaluation

The conclusion drawn from the analysis is that the overall project didn't meet the specification as it failed to successfully control the temperature within the house.

All of the objectives were complete and a fully functioning prototype was constructed. A designed and fully built circuit board was created to operate the project as shown below in figure 8. The only factor to of failed was the control valve signal from the PID controller.

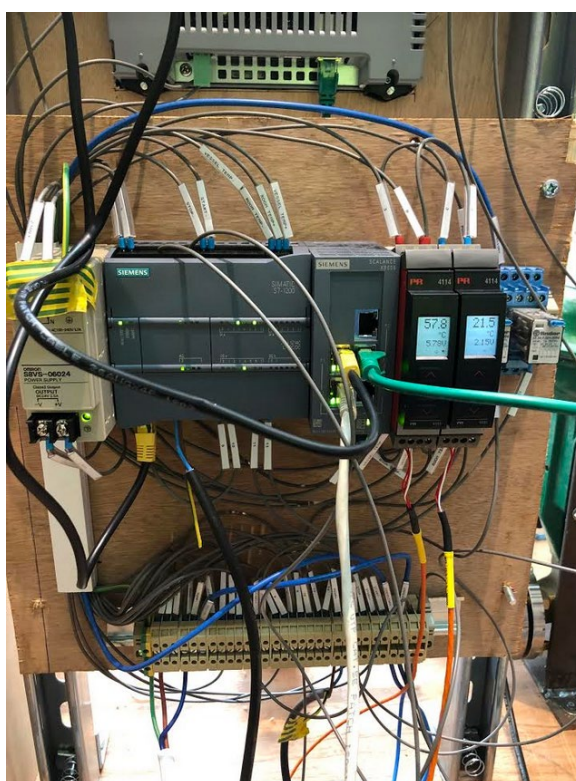


Figure 85 - Control Circuit Panel

A mass of research was carried out into potential items of equipment used for this project such as temperature sensors, type of control valve and valve positioners any many others. Each item of hardware and software chosen worked to its requirements. With HMI screens constructed along with the PLC program the prototype was user friendly and can be operated by anyone.

Testing was performed as results were gathered to see how hot the room temperature could get with the vessel temperature at different points such as 40, 50 and 60 degrees. Also the need for testing the both room and water vessel temperatures to the HMI proved to be a challenge as trial and error had to happen until the right division value was found.

Chapter 8 – Conclusion

To conclude the whole project each chapter is to be explained.

Chapter 1 – Introduction

Within the introduction information is delivered about the chosen project and gives the reader a good insight into what the project is capable of achieving. A system diagram is there to help the reader visualize the project, this should also aid in getting a better understanding about the project. The introduction is kept short to give the reader a quick insight.

Chapter 2 – Planning

Project objectives and project milestones are covered in chapter 2 creating a timescale to alert the reader what needs to be completed by each date. A gantt chart is there to expand the timescale including specific points. The project breakdown dates have changed due to a late change in project. The previous project proposal was eliminated because the cost of the project would of cost too much and seemed far to complex. Due to work commitments the breakdown dates are very close to the project hand in date. The project has taken a lot of time to construct by leaving my time was needed.

Chapter 3 – Research Methodology

By delivering different methods of research to the reader it helps to develop the understanding of the research methodology. A deductive research approach due to the project being something new which no one had really created before. Research gathered seriously helped into what the objectives of the project were going to be. The experiment method was used when designing and constructing the project and also when testing and fault finding.

Chapter 4 – Market Research and Investigation

The research and investigation chapter contains a lot of information on what's currently on the market that's similar to this project. Comparison between possible hardware to be used and also comparison between the current ways of heating. A lot of information referring to each item of hardware such as sensors and materials. A detailed description on each item of hardware and also why the particular hardware had been chosen to be used are within this chapter. After researching the current methods on the market, possible solutions to make this project work were derived. An insight into possible methods of control is shown to again give the reader a much greater understanding. Chapter 4 overall really set tone for project because it being such a big chapter once completed the implementation stage can begin.

Chapter 5 – Design and Implementation

The design and implementation of the control circuit panel including loop drawings found in the appendix are described chapter 5. Pictures of the finished prototype are shown as well as the 4 HMI screen designs which are actually visible on the prototype. A build cost is included to breakdown the costing of each part used, an accurate figure is shown stating how much the prototype costs. The PLC ladder program can be found under the heading 5.2, each network has a brief description on how the ladder operates. Having a program block which can be found at point 5.3 aids the reader in how the PLC is set up to operate, showing the direction of travel of the individual signals making it easier to identify what is a digital input, digital output, analogue input and analogue output.

Chapter 6 – Analysis

Chapter 6 is where 3 tests occurred on the prototype. Test 1 was to collect data on the max temperature the house could get when the control valve is fully open at different vessel temperature set points. As concluded 60°C the water vessel needs to be to get the best results. Test 2 was to convert a hexadecimal value to a decimal value to prove that the line of ladder is correct. Due to the initial vessel and room temperatures not matching the HMI values a correct division figure needed to be calculated. Test 3 is the configuration and commissioning of the PID block to give three term control action on the temperature control valve. The test was a failure due to a number of factors as discussed in chapter 9.

Chapter 7 – Evaluation

The evaluation summarizes the end results of the project. The evaluation checks to see if the objectives were completed and all specifications were successful. To conclude the most of the objectives were completed by overall the project was a failure because change in temperature in the house took far too long to rise and far too long to cool.

Chapter 9 – Reflection

A lot of time and effort was put into this project to not only to design the PLC program and the HMI display screens but to actually build a full semi working prototype that apart from the control action not working as it should be everything else about the project was a great success. What would be discussed in the reflection is the faults and errors the author achieved throughout the project and also ways of improving the project.

Fault 1 – Not Being Able to Go Online Mode

When commissioning each loop individually a number of errors occurred. To start the process all the alarms must be healthy and the LEDs must be green. When the system was first powered up all the alarms were healthy by the 'Alarm LED' was unhealthy. Looking through the lines of ladder logic and no fault was visible. On TIA 3 programming software there's a function which allows the user to go 'Online Mode'. Going online means the user gets to see what exactly is happening in the programme. All the raw analogue and digital signals can be seen so it's a great tool for fault finding. So after being online mode and still not understanding why 'Alarm Active' (Network 3) is in an unhealthy state a phone call to Siemens Support was made. After speaking to a member of Siemens technical advisors he said that unless both the offline program and the online program are exactly the same then what is being seen in the online program is not true. The advisor recommended to download the program to the device when offline, then to go online and download to device again, this way the exact same program is being seen in both states. The advisor also said that if any of the ticks as on the left aren't green, the offline and online program are different. By following the advisors instructions the fault had corrected itself allowing for further tests to continue.

Fault 2 – Incorrect Sized Cable for Immersion Heater

When first builds of the prototype began the immersion heater was wired using 0.75mm flexible twin and earth cable. Only by chance when loop checking after picking up the cable the author noticed that the cable was hot. After doing a calculation to see how much current the immersion heater took which was 13.03Amps the cable was clearly not rated to handle that much current. By performing research the cable was changed to 1.5mm flexible twin and earth which was then suitable. As shown below.



Figure 86 - 1.5mm Immersion Heater Cable

Fault 3 – Incorrect Analogue Output Range

Having thought the analogue output module from the PLC could output 4 – 20mA a fieldvue positioner was used to operate the control valve. Only when commissioning each loop the output range to the control valve was 0 – 20mA. This was a big error because the positioner being used only operated between 4 – 20mA. This meant that when the PLC is asking the valve to be 4mA open it physically would be fully shut. A way to get round this would be to adjust the zero calibration of the positioner making the valve slightly open at 4mA. This creates a knock on effect because this would mean that the valve would never be able to fully shut unless it loses its air supply. If the supply air is lost the spring would force the valve fully shut. Again by adjusting the zero calibration it would affect the top end calibration potentially making the valve more open than it should be. Reflecting on the fault if more time was available PLC ladder could have been created to move the signal by dividing the raw signal by a known value. So as the instead of having a 0 – 20 range the output could be 4 – 20. Also another way this could be solved is to add an extra PR 4114 universal transmitter to take in the input and to output 4 – 20mA. This would cost more but would save time with programming.

Fault 4 – Heat Loss

This project is a complete system with the water getting heated in the vessel, pumped out through the copper coils and returned back into the top of the vessel. A lot of power is used to keep the vessel hot at 50 degrees. By placing a lid on the open vessel and insulating with rock wool it the heat would stay trapped inside the tank. As a result of this the immersion heater would be on less frequently therefore saving on power. By insulating all the copper pipes as well less heat would escape.

Fault 5 – Not Enough Heat

Having insulated the wooden house to trap the heat even with 3 10mm copper coils containing 7 coils each it still wasn't enough to achieve heat the wooden house to the desired temperature. The problem was that there wasn't enough surface area from the copper coils to emit the heat. The water entering the coils was exactly the same exiting the house. Not releasing until late that the copper coils needed to be much larger to create a bigger surface area so more heat can be emitted. Fans were installed under the copper coils to help heat transfer by blowing cooler air against the coils to help radiate the heat. Ultimately this was the main reason why the project wasn't a complete success. A number of improvements could be installed to help achieve success as listed below.

- Increase copper coils size to emit heat.
- Larger and more powerful fans to help cool the coils.
- Use smaller copper pipes so more coils can be created.
- Improve Insulation.

Fault 6 – Latching Start and Stop Button

To start the prototype requires the start button to be pressed. In network 1 on the plc program by pressing the start button the system should start and kept latched on once the button has been released. Whilst going through the available switches in BOC Gases the only start and stop buttons available where latching. Having thought that these buttons would be suitable because once the switch was pressed in making the switch, if it was to be pressed out again it would be the same as a non-latching switch. Come starting the prototype it wouldn't start. Having going online mode on the laptop it was clearly shown that for both the start and stop buttons had to be pressed in to start the process. To stop the process the stop button needed to be pressed again. New switches were then ordered and fitted to the prototype which resolved the issue.

Fault 7 – Pump Loss of Prime

After each day of testing the prototype was switched off. So when returning the next day once powered up and was asked to start the system would become operational, but the flow of water back into the tank was very little. Even when the control valve was fully shut and the bypass valve was fully open the flow of water was still minimal. Having researched online into the problem the pump in the prototype was mounted in a horizontal position meaning that it had the potential to have trapped air in the system. So with the pump running the bleed valve was open and air was felt exiting the valve. Once the air was released the pump was re primed and the water flow increased back to normal running condition. Ways of eliminating this problem would be to mount the pump in a vertical position so that water is always kept in the pump.

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Appendix

Datasheets

Immersion Heater

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Temperature RTD PT100

<https://docs-emea.rs-online.com/webdocs/1591/0900766b81591b90.pdf>

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file:///C:/Users/1708879/Downloads/6ES72141AG400XB0_datasheet_en.pdf

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https://www.automation.siemens.com/salesmaterial-as/brochure/en/dffa-b10135-01-7600_ipdf_simatic_hmi_en.pdf

Omron 24V Power Supply

<https://docs-emea.rs-online.com/webdocs/1378/0900766b813786d0.pdf>

Finder 24V Coil Relay 7A

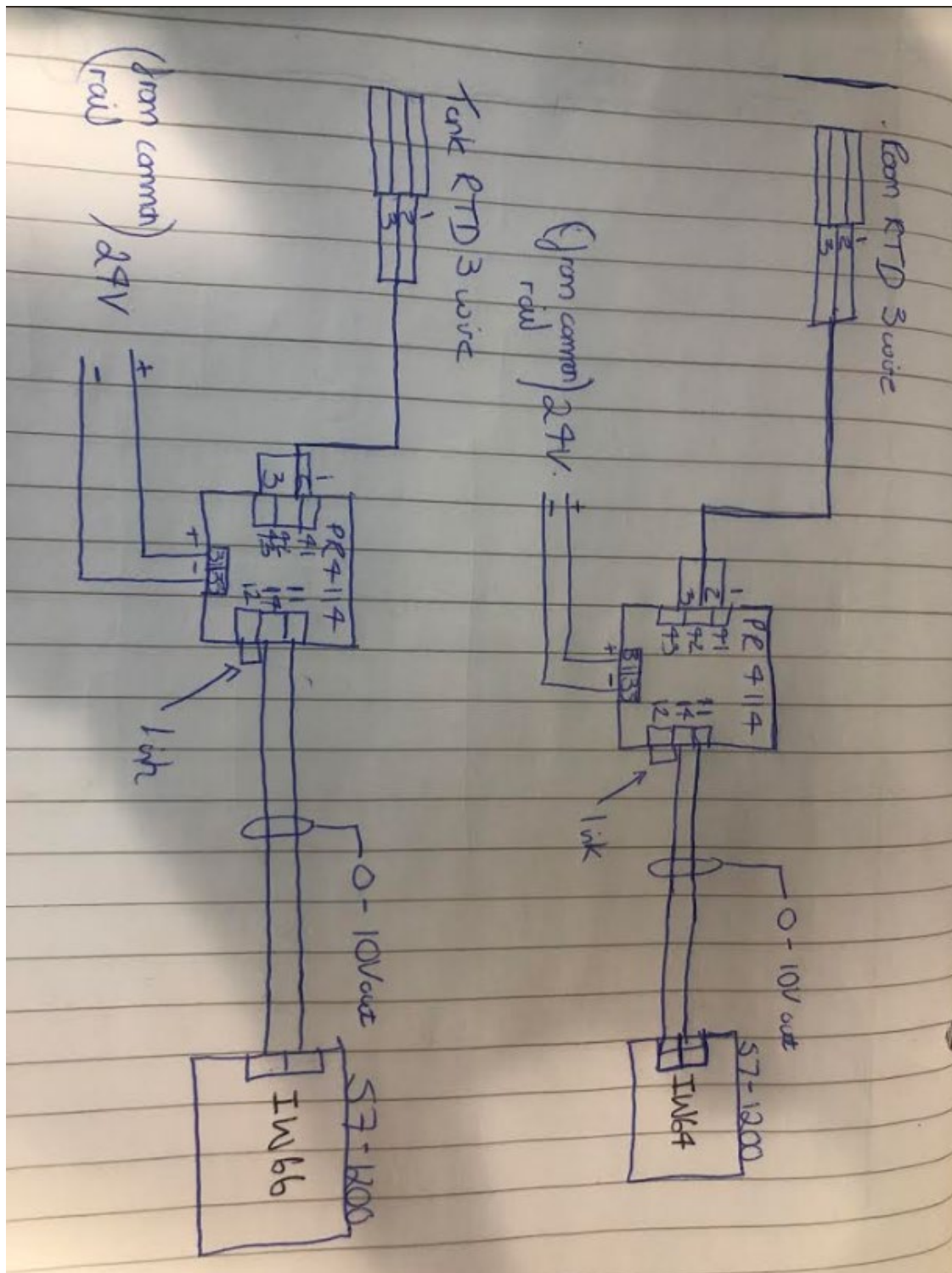
<https://docs-emea.rs-online.com/webdocs/16d5/0900766b816d51a5.pdf>

PR Universal Transmitter 4114

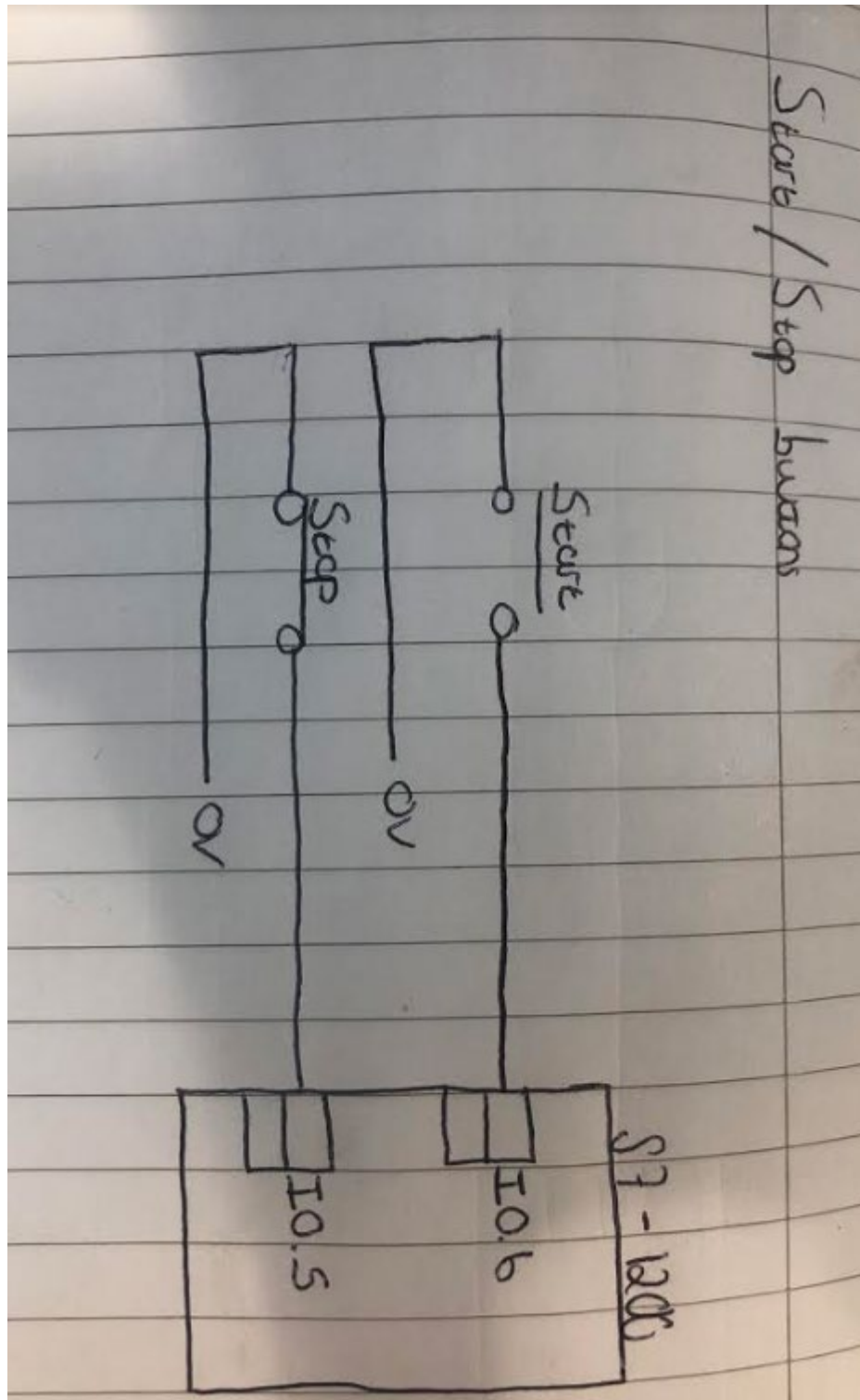
<https://www.prelectronics.com/pdf/4114-2270-US.pdf>

Loop Drawings

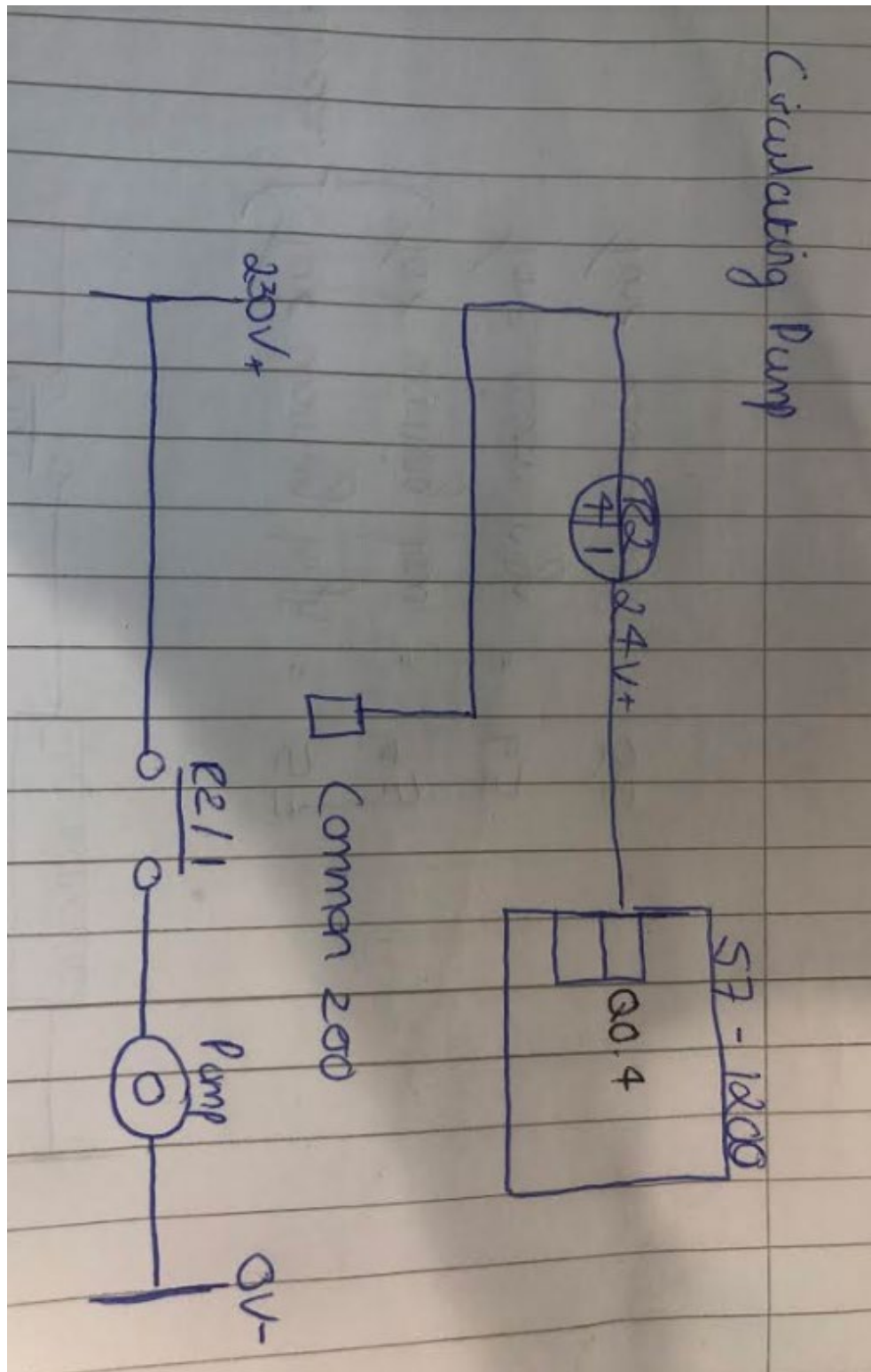
Room and Vessel Temperature



Start and Stop Circuit



Circulating Pump



Immersion Heater

