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Fault Detection System for Solar Tracking Applications

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FAULT DETECTION SYSTEM FOR SOLAR TRACKING APPLICATIONS

by

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ABSTRACT

FAULT DETECTION SYSTEM FOR SOLAR TRACKING SYSTEMS

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Oil, coal and natural gas reserves are being depleted faster than forecasted due to continued increase in demand for energy sources. We need, therefore, to develop renewable energy sources, such as solar, wind, biomass, geothermal, hydro power and tidal energy. In spite of having very high potential, harvesting solar energy has been a challenge because of the relatively low efficiency of solar cells. In the past few years different methods have been developed to increase the efficiency of the photovoltaic (PV) system: (i) improve the efficiency of solar cells (ii) use a solar tracking system to increase the received solar radiation on the modules.

For a photovoltaic tracking system, the amount of power generated by the solar trackers is monitored by the inverters, which monitor the power of up to 100 trackers each. If there emerges a situation where the power output of a certain inverter decreases when compared to the average, it then becomes really difficult to predict or judge the source of the problem. So, in order to determine the root cause of the reduction in output power, each and every tracker is supposed to be tested. A good solution to prevent this problem is to use micro-inverter systems with lower capacities which handle inputs from fewer trackers. This would, however, increase the total cost of the project by a large margin.

We have therefore proposed and developed a solution for the above problem which is both cost effective and easy to use. We built a fault detection system which

monitors the variations in the current and voltage of each individual tracker and relays that to the on-field controller. This system can monitor the above mentioned parameters of several photovoltaic trackers (currently designed for fourteen trackers) using one Programmable Logic Controller. Furthermore, this system helps in comparing the performance levels of the inverter which has the input of the combined trackers with that of a single tracker. The data provided by this system can also help in making a deep analysis of the decreasing efficiency over a period of time.

dedicated

to my parents Soma Sekhara Rao and Vakula Sri

and my brother, Naveen Sekhar

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CHAPTER 1

INTRODUCTION

1.1 Background:

The two biggest concerns of conventional sources of energy today are their increasing rate of depletion and the amount of pollutants being released by them during combustion and generation. This is the prime cause of increasing greenhouse gases which in turn are causing global warming [4]. The increasing demand for energy is forcing the authorities to put a high price tag on the conventional sources such as oil, coal and gas. Nearly 81% of the energy production is now dependent on conventional sources of energy [4, 10]. It has been predicted that in the near future the demand for energy will grow to such an extent where it will be almost impossible to meet demands due to ever depleting resources. This poses an open and positive challenge to the whole scientific community for research and development of new efficient alternative energy sources which may meet the growing demand and pave the way for clean and cost effective development mechanisms.

Non-conventional sources of energy like biomass, solar, wind, geothermal and tidal will need to play an important role to meet the increasing demand as well as replace the conventional source. Among these sources, energy from the sun is unique and abundant. The sun is a natural source which is expected to last for another 4 billion years. Solar photovoltaic (PV) power is a method where the energy from the sun is converted into electricity. The photovoltaic systems have an estimated lifetime of 25-30 years. At present, the photovoltaic systems have an average conversion efficiency of 14%. More and more funds are being allocated and invested in research related to solar power, especially to increase the conversion efficiency and make them cost effective so that these would be accessible at a low cost to all people throughout the globe.

In this context we have concentrated our research on solar tracking technologies. Solar tracking is the concept of tracking the sun and orienting the PV modules towards the sun. Our area of research was focused on developing a cost effective health monitoring system of the PV modules used in a solar tracker.

1.2 Thesis Organization:

Currently, efforts are being made to increase the efficiency of the photovoltaic systems, both in the solar cell manufacturing stages and in their respective applications. In this thesis research, the aim is to understand and develop a fault detection system for monitoring various parameters associated with the solar tracking applications.

In Chapter 2, a detailed explanation of the photovoltaic system has been provided. It also contains concepts related to the solar photovoltaic power scenario, characteristics of solar cells and the various solar tracking systems.

In Chapter 3, the working of the solar tracking system has been explained. The chapter also contains a detailed explanation of our problem statement.

Chapter 4 contains a detailed explanation of the design and fabrication of the fault detection system.

Chapter 5 contains an explanation of the experimental set up and the various test results followed by the last chapter which concludes the thesis and gives future recommendations for the project.

CHAPTER 2

PHOTOVOLTAIC SYSTEMS

2.1 Photovoltaics

2.1.1 Introduction

Oil, coal and natural gas reserves are being depleted at a rate faster than forecasted due to continued increase in demand for energy sources. These will soon require replacements to satisfy the global energy demand. Coal is expected to last longer when compared to oil and natural gas, but the decrease in demand of these would multiply the demand for coal in the coming years [11], so there is an immediate need for us to switch from fossil fuels to non-conventional or renewable energy resources. Moreover, combustion of fossil fuels leads to the emission of toxic greenhouse gases [11] like the oxides of carbon, nitrogen and sulphur which are the main reasons for global warming. This is one major problem the world is facing now. Nuclear energy was expected to be a good alternative as it does not produce greenhouse gases, but it is still considered dangerous because of the toxic waste produced, which continues to be radioactive for at least 10,000 years [11]. The best and safest way to reduce or reverse greenhouse gas emission levels is by switching to renewable energy sources.

Renewable energy is a form of energy which comes from natural resources. The most common sources of renewable energy are solar, wind, biomass, geothermal, hydro power and tidal energy. Energy needs are escalating with the continued industrialization and increasing population. The need for efficient renewable energy sources to maintain a balance for the demand and supply is gaining prominence. It is estimated that renewable energy sources supplied almost 16% [10] of the global energy demands in 2009 whereas they have accounted for nearly 19.4% in 2010 [10].

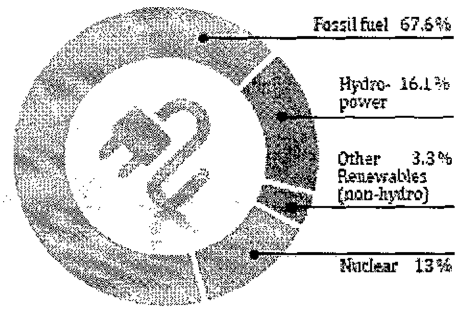

Fig 2.1 Renewable energy share in global electricity production [10]

2.1.2 Solar Insolation and Photovoltaic Power

Insolation is a measure of solar radiation on a given surface area during a specific time. It is also known as *solar irradiance.* Solar photovoltaic power output is directly dependent on solar irradiance over the solar panels in a given location during the day [9, 11]. This value alters significantly depending on the geographical location, sun's angle, season, amount of cloud cover and dust particles which can prevent the sunlight from reaching the solar panels and ground. Solar panels are known to give maximum output efficiency when they are perpendicular to the sun [1, 4, 11], where they can get maximum solar irradiance.

Photovoltaic (PV) technology generates direct current (DC) electrical power from semiconductors when they are illuminated by light. Each individual photovoltaic element is known as a solar cell. As long as light is supplied to the solar cells, they generate output power. To extract maximum efficiency of a solar cell they are supposed to be exposed to high solar insolation levels. The average insolation levels in the US are between 3 and 7 kW/m^2 [11].

2.1.3 V-I Characteristics of Solar Cells

A solar panel consists of numerous solar cells which are nothing but semiconductor devices. Silicon is the most commonly used semiconductor material [11]. The main reason for using semiconductors is the ability to control their conductivity unlike the conductors and insulators. The electrons in these semiconductor materials are located both in the conduction band and the valence band. When a source of light strikes the semiconductor material, the electrons will acquire enough energy to move from the valence band to the conduction band and because of this a positively charged hole is created in the valence band. As soon as this happens, the electrons from the conduction band begin to move freely creating a flow of charge [11]. But the valence band is no longer full due to the presence of holes. These play a vital role in the current flow. These semiconductor materials have impurities added to them through a process known as *doping*.

Every solar cell has its unique voltage-current (V-I) characteristics. The Fig 2.2 shows the I-V characteristics of a typical solar cell.

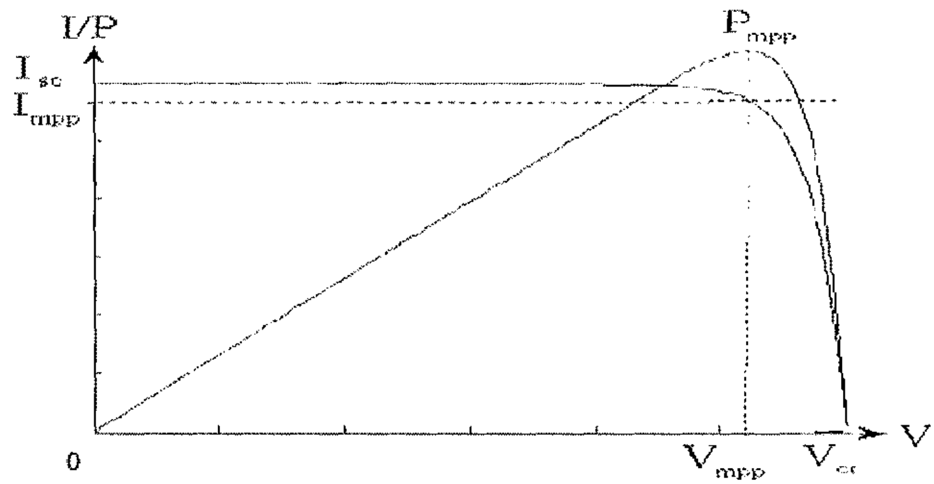

Fig 2.2 Current-Voltage (I-V) characteristics of a solar cell [4]

Two curves are depicted in the figure above. One shows the variations of current with respect to the increasing voltage, and the other curve shows the power-voltage (P-V) curve. It is evident that the relation between the current and the voltage is non-linear. The major problem with extracting the maximum power out of the solar panel is due to this non- linearity in the V-I characteristics. Observing the V-I curve and the P-V curve, maximum power is obtained at a certain point known as the *maximum peak power* (MPP). In order to obtain peak power from a solar panel, it is required to be operated at the MPP.

Factors such as solar irradiance and temperature levels which change frequently alter and change the MPP regularly. Therefore, a constant monitoring of the P–V curve is required to obtain the maximum output power from the PV systems.

An increase in the insolation levels brings a positive increment to the MPP and eventually increases the peak power output. The Fig 2.3 illustrates the effect of insolation on the V-I characteristics.

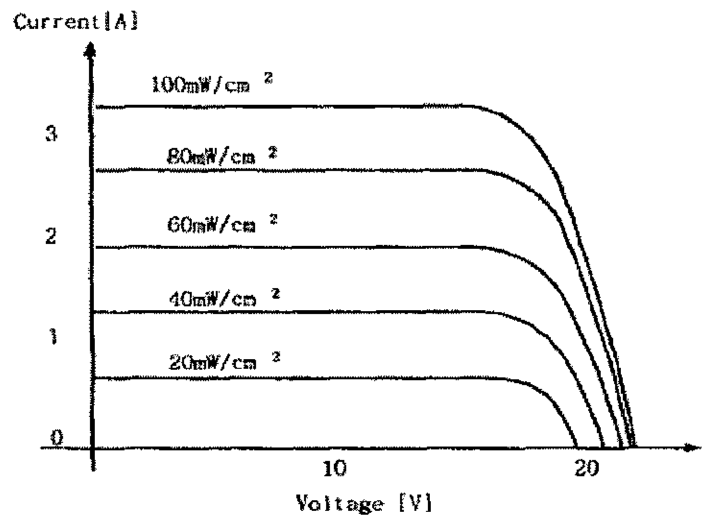

Fig 2.3 Effect of Solar Insolation on V-I characteristics [12]

Temperature, too, has a great effect on the performance of the PV systems. At higher temperatures there is a drop in the voltage level which shifts the MPP causing a reduction in the power output [12]. The Fig 2.4 illustrates the effect.

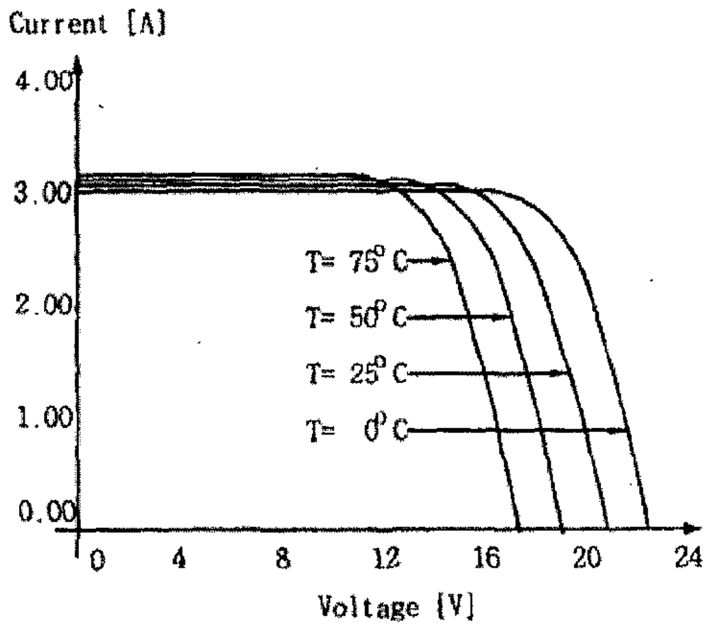

Fig 2.4 Effects of temperature on V-I characteristics [12]

Fill factor (FF) determines the efficiency of the solar cells. It is the ratio of the output power (power at maximum peak power point) and the product of the open-circuit voltage (V_{OC}) and short circuit current (I_{SC}). Typically, the value of FF ranges from 0.7 to 0.85 [11, 13]. This is an important parameter in the long run.

2.1.4 Efficiency of PV systems

When PV systems are offered to the commercial market, the efficiency of the solar cell, as well as the cost, are important parameters. Efficiency here refers to the conversion efficiency of the PV modules. Conversion efficiency is defined as the ratio of the total output power to the total input power. Commercial solar modules have energy conversion efficiencies in the range of 12-14% [13].

PV systems lose output over time due to the combination of any of the following factors namely Light Induced degradation (LID) and Long term degradation LID is an irreversible loss of 1-3% of output power which occurs due to the presence of oxygen impurities that get trapped during the ingot formation process.

Long term degradation applies universally among the PV technologies. A decrease in 0-2% of annual power output is observed with most on the range of 0.3-1% [11]. Most of the lower 0.3-0.5% data is primarily associated with the modules, and 0.5-1% range is associated with the system.

2.1.5 Solar PV Power Scenario

Solar PV power (Solar energy) has gained a lot of prominence in the past few years. Solar energy has contributed nearly 40 GW [10] in 2010 globally and is growing at a very rapid rate. It is known to be the fastest growing power generation technology across the globe. Fig 2.2, 'Solar PV existing capacity', illustrates the enormous rise in power generation over the years.

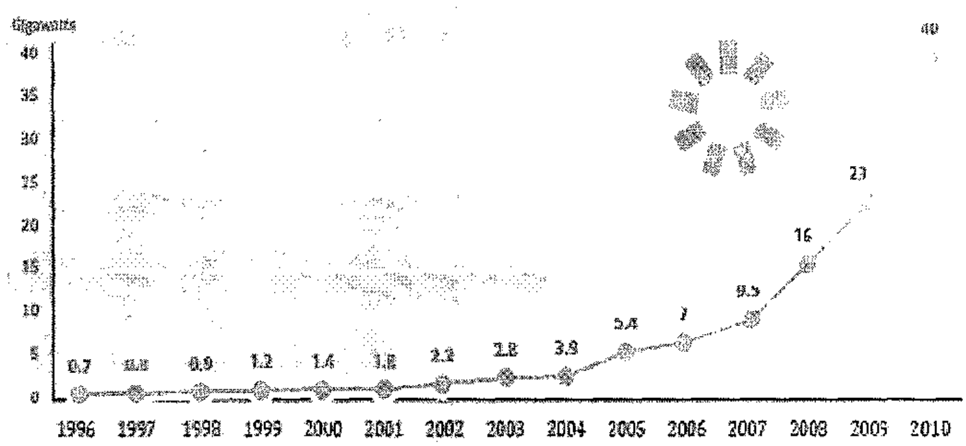

Fig 2.5 Solar PV existing capacity and growth trend [10]

Analyzing the above data, the solar generation capacity stands at 40 GW and has increased by almost 72% in 2010 compared to 23 GW in 2009 [10]. This rise was driven primarily by the dropping prices of solar cells manufacturing costs, more investments, various new applications and continued strong policies to harness renewable power.

2.1.6 Advantages of Photovoltaics

1) The source of fuel, sunlight, is vast, widely accessible and almost infinite.

2) They have no harmful emissions or wastes. Hence, these do not contribute negatively to the global climatic changes and pollution.

3) They have very low operating and maintenance cost after initial setup.

4) They are reliable and are expected to last a minimum of 25 years.

5) They can be integrated into existing or new buildings.

6) Grid connected solar power can be used locally which helps in reducing the transmission and distribution losses.

2.1.7 Disadvantages of Photovoltaics

1) Solar electricity has rather high initial setup cost.

2) Unpredictable hourly or daily outputs. These are highly dependent on weather conditions.

3) Since no power can be generated during the night, they require very efficient storage systems. Storage systems increase the initial cost of setup.

4) They require approximately 2 hectares of land for generating 1 MW of power.

2.1.8 Applications of Photovoltaics

1) In transportation, they are used to supply auxiliary power in space, cars and boats.

2) They are used in a few countries at electric car charging stations.

3) They are now commonly used for street lighting, at traffic signals, emergency telephone booths on highways and many more.

4) They are used to power standalone devices such as calculators, watches and other novelty devices.

5) They are used to support small off- grid DC and AC systems.

6) They are also used in On-grid systems where the energy produced by the PV modules is converted to AC power and either used on-site or injected into the utility grid.

7) They can be utilized as Hybrid PV systems where the PV systems are used in conjunction with one or more auxiliary power sources.

2.2 Tracking systems

2.2.1 An overview

In spite of having very high potential, harvesting solar energy has been a big challenge because of the relatively low efficiency of solar cells. In the past few years different methods have been developed to increase the efficiency of solar cells and panels. There are many factors that actually limit the conversion efficiency of a solar panel. A few among them are weather, operational conditions, land geography, etc. There are two possible solutions to optimize these factors: i) improve the efficiency of the solar cells ii) use solar tracking systems to increase the received solar radiation on the modules [5].

The majority of the solar modules around the world are fixed mount. When it comes to large scale production, most of them are fixed facing South-East if they are in the northern hemisphere and North-East if they are in the southern hemisphere [5, 11] with a certain tilt-angle. As the day progresses, the position of the sun changes and will no more be facing the solar panels, thus, the output power from the panels decrease gradually. This is one of the major drawbacks of the fixed mount solar panels. This drawback can be overcome by using solar tracking systems which orient towards the sun throughout the day.

2.2.2 What is a Solar Tracker?

A solar tracker is a device that can be oriented towards the direction of the sun throughout the day. These trackers can be fixed with many solar panels, modules, reflectors or lenses. Solar panels are known to work effectively when facing the sun [1, 4]. The main objective of using a solar tracking system is to effectively capture the sunlight throughout the day to optimize the output. Solar tracking systems produce more output power because the solar panels track the maximum power point of the sun's position [6]. These trackers increase the output power by a large number compared to fixed mount or stationary panels.

2.3 Different types of Trackers

1) Horizontal axis Tracker.
2) Vertical Axis Tracker.
3) Dual Axis Tracker.
4) Azimuth-Altitude Dual Axis Tracker.
5) Multi-Mirror Concentrating Tracker.
6) Active Tracker.
7) Passive Tracker.
8) Chronological Tracker.

2.3.1 Horizontal axis Tracker

In this type of tracking system, the solar panels are placed on a long rod extending itself in the North-South direction which is the axis of rotation and is elevated at a certain height. These trackers rotate in the East-West direction, which is the direction of the movement of the sun throughout the day. The main advantages of this system are its simplicity in its working mechanism, its design, and the fact that the low elevation height of the panels makes them accessible for cleaning and also reduce the risk of self-shading. Multiple rows of solar panels can be controlled using a single motor and a single control unit. These trackers are most effective in the summer and spring seasons. Since these trackers are not oriented towards the equator they have reduced efficiency in winter. Moreover, these are less effective at higher altitudes.

2.3.2 Vertical Axis Tracker

In this type of tracking system, the axis of rotation of the solar panels is vertical with respect to the ground, and the face of the modules is oriented at a certain angle along the axis of rotation. These are primarily used at higher altitudes. The trackers here rotate in the East-West direction. The layout of the field must be well planned to avoid self-shading which reduces output efficiency.

2.3.3 Dual Axis Tracker

Dual axis trackers rotate both in the horizontal direction as well the vertical direction. The axis which is fixed with respect to the ground is the primary axis and the one normal to it is considered the secondary axis. These systems have higher output efficiency compared to other systems as they follow the sun at any point of time throughout the year, but the cost of these systems is a limiting factor. Dual axis trackers are controlled by a master controller, and each unit will have a dedicated computer controlled motor.

2.3.4 Azimuth-Altitude Dual Axis Tracker

In this type of tracking system, the primary axis is perpendicular to the ground, and the secondary axis is normal to it. The horizontal axis is known as the Azimuth which allows the movement of the modules in the upward and downward direction. The vertical axis is known as the Altitude which allows the circular motion of the modules. In these systems the mounting is done in such a way that the whole weight of the solar modules is supported using a large ring mount consisting of a series of rollers on the ground. The main advantage of these systems is that weight distribution is even and spread across the ring mount. These systems are suitable to support large array systems, but these systems require a lot of space and should not be placed close to each other to avoid self-shading.

2.3.5 Multi Mirror Concentrating Tracker

In this type of system, multiple mirrors are used in a horizontal plane to focus the sunlight on to a concentrator. These concentrators can be either a photovoltaic system that requires high temperatures or tower-mounted thermal receivers that convert water into steam and later send that to a steam turbine which generates electricity. The steam is later condensed and sent back to the receivers. These systems are generally used on flat surfaces.

2.3.6 Active Tracker

In this type of system, motor and gear trains are used to orient the trackers. A controller which tracks the movement of the sun is used to control these motors. Slewing drives are one of the latest devices that can produce high torques and can move both along the horizontal as well as the vertical axis. These systems are very slow to respond, and dependence on factors such as ratio of worm threads on the worm to the number of teeth on the gear limits their use.

2.3.7 Passive Tracker

These systems use compressed gas fluids that have low boiling points. These gas fluids expand and contract with variations in temperature which in turn develops pressure inside the gas tubes thus making it move. They are designed in such a way that they move in the direction opposite to the movements of the fluids. They use dampers to prevent excessive movement of the fluids in case of winds or sudden change in temperatures.

2.3.8 Chronological Tracker

In this type of system, the tracker counteracts the rotation of the Earth at almost the same rate but in the opposite direction. The drive mechanism uses a gear motor that moves continuously throughout the day.

2.3.9 Comparison of output efficiencies

The solar tracking systems are one of the best methods to improve the conversion efficiency of the output power in a day. The systems show their prominence as they move away from the equator either into the northern hemisphere or southern hemisphere.

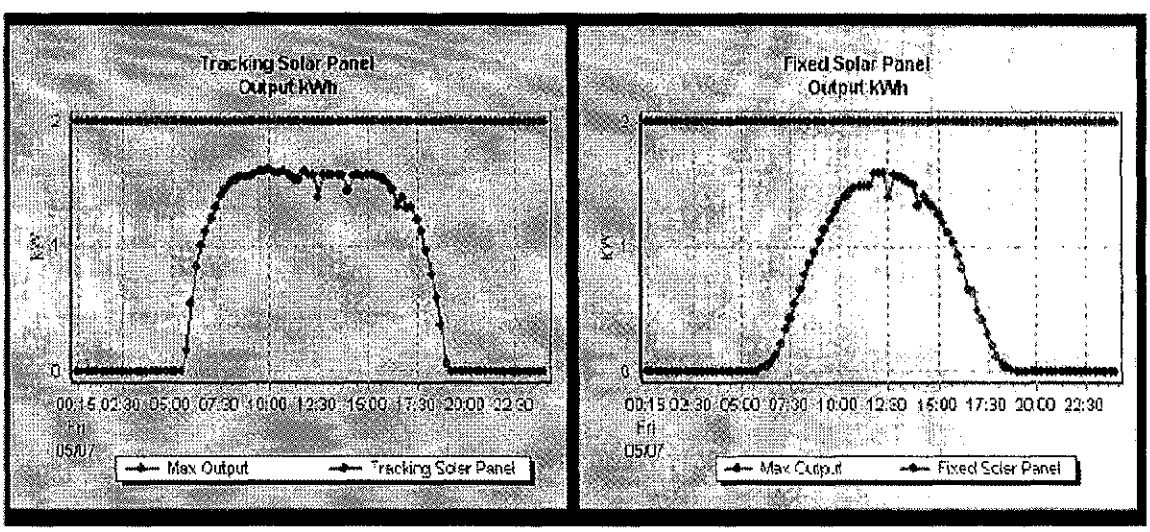

Fig 2.6 Comparison of conversion efficiencies for fixed mount and dual axis tracking systems [5]

As mentioned previously, when we compare the conversion efficiencies of a fixed mount system and a dual axis tracking system, the output of the dual axis system is much more efficient compared to the fixed mount system under similar conditions. They have higher conversion efficiency, and this value increases between the range of 30-60% [5, 6, 7 and 11]. When we compare the curves in Fig 2.6, it is seen that the dual axis tracking system has more area under the curve compared to the fixed system, which means more power is generated using the tracking systems. It is also observed that there is an increase in power generation when the sun's position is near sunrise and sunset in the dual axis tracking system.

2.4 Tools Used

2.4.1 Programmable Logic Controller (PLC)

Programmable logic Controllers (PLC) are microprocessor based controllers used for automated control of several devices and machines. PLCs are designed to control multiple inputs and outputs in a very short interval of time. The term logic is used here because programming is concerned primarily with implementing logical and switching operations. These devices have been developed to replace the relay control systems which consist of a series of relays, timers and drum sequencers.

Relays use an electromagnet to control the switching mechanism mechanically. In order to control multiple devices with varied functionalities, a large number of relays are required, and they consume a lot of space. Moreover, relays are mechanical devices and are subjective to wear out which forces them to be replaced very often. These drawbacks of the relays led to the development of PLC.

PLC have a wide range of functionality which includes sequential relay control, distributed control systems, motion control, networking and many more. These devices have capabilities similar to ordinary computers in terms of processing capability, data handling, data storage and communication capabilities. They can facilitate a large number of input/output (I/O) arrangements which can be directly linked with the PLC or use an external I/O module.

These use a programmable memory to store all the instructions and implement functions such as timing, sequencing, logic and arithmetic. There are various memory elements in a PLC that help in performing the tasks and reducing the operation times of the instructions [14].

Read Only Memory (ROM) is a fixed memory and is used for the permanent storage of the operating system and other data related to the functioning of the controller. *Random Access Memory* (RAM) is used for the user defined program and also for processing the data related to the program and status of other connected devices. A part of this memory is set aside exclusively for addressing the devices. An additional module, *erasable and programmable read only memory* (EPROM) may be added if required to enhance the performance of a PLC. A small battery is used to prevent the loss of RAM data for a certain period of time to prevent the loss of downloaded programs when the power supply is switched off.

The *Input/output (I/O) unit* provides the interface between the processing unit and the output devices through a series of I/O slots or channels. Every input and output slot has a specific and unique address. The I/O unit also performs the tasks of signal conditioning and isolation which help output devices like actuators be directly connected to the PLC. This omits the need for additional circuitry. A 5V DC signal is generally compatible with the microcontroller of the PLC. Along with isolation, signal conditioning allows a wide range of such input signals. The Fig 2.7 illustrates various possible inputs [14].

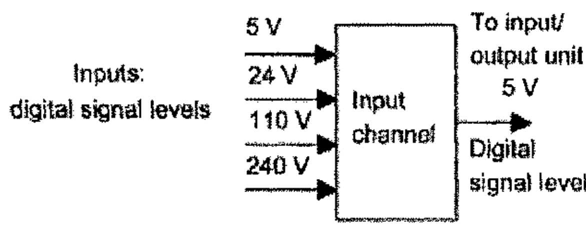

Fig 2.7 Input levels to the I/O unit [14]

The output from the I/O unit to the output channel is 5V. After signal conditioning with the help of relays, transistors or triacs, the output from the channels may be increased to 24 V at 100 mA switching signal. With the help of modular PLC, a wide range of such outputs can be accommodated by selecting different modules. The Fig 2.8 illustrates various levels possible through the use of modular PLC [14].

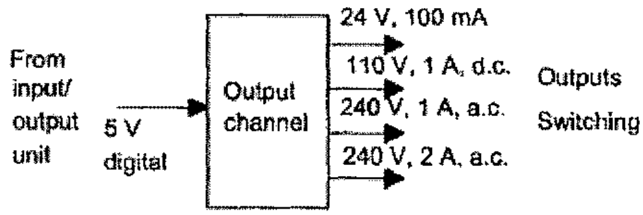

Fig 2.8 Output levels from I/O unit

When there are many inputs or outputs located at considerable distance away from the PLC, it is possible to connect them individually using cables. A much easier and economical way would be to connect all inputs and outputs to one I/O module and connect that to the PLC. They can also be connected wirelessly. but that would not be economical in all conditions.

User defined programs for the microprocessor based systems have to be downloaded into the machine code which is a sequence of binary numbers. There are different types of programming languages. Ladder logic and functional block programming are most commonly used because of their ease of use [14]. Other programming languages include instruction lists, sequential function charts and structured texts.

2.4.2 Modbus Communication

Many output devices can be controlled at one time using the daisy chain, ring, mesh or tree topology. *Modbus serial communication protocol* is one of the best ways to control and communicate to multiple devices in a given network. It is a simple yet robust design. It has been designed keeping industrial applications in mind. It can communicate with up to 246 devices connected through a single network. Each device is assigned a specific and unique address. It is basically categorized as a master-slave communication. A Modbus command contains the address of the device, and only that particular device responds to the command. Broadcasting is also possible through this protocol.

2.4.3 Actuator

An actuator is a type of motor which uses electrical energy and converts that energy into a particular motion. Actuators are known to be a sub division of transducers. Mechanical, hydraulic, pneumatic, piezoelectric, electromechanical and telescoping actuators are different types of actuators. Linear actuators are most commonly used for solar tracking application. These actuators can be controlled using either Modbus or Profibus communication. These have very high *push* and *pull* load capacity.

2.4.4 GPS

Global positioning system (GPS) is a satellite based navigation system that can provide data related to a location like latitude and longitude, time and many more. These are used in solar tracking systems to locate the exact location of trackers and their longitude and latitude positions. GPS systems are also preloaded with algorithms that can exactly determine the sunset and sunrise times on a given day.

CHAPTER 3

SOLAR TRACKING SYSTEMS

3.1 Working of a Solar Tracker

A solar tracker is a device that can be oriented towards the direction of the sun throughout the day. The solar tracking system on a whole consists of a solar tracker, actuator, controller, communication cables, and GPS. A block diagram of the solar tracking system is shown in Fig 3.1.

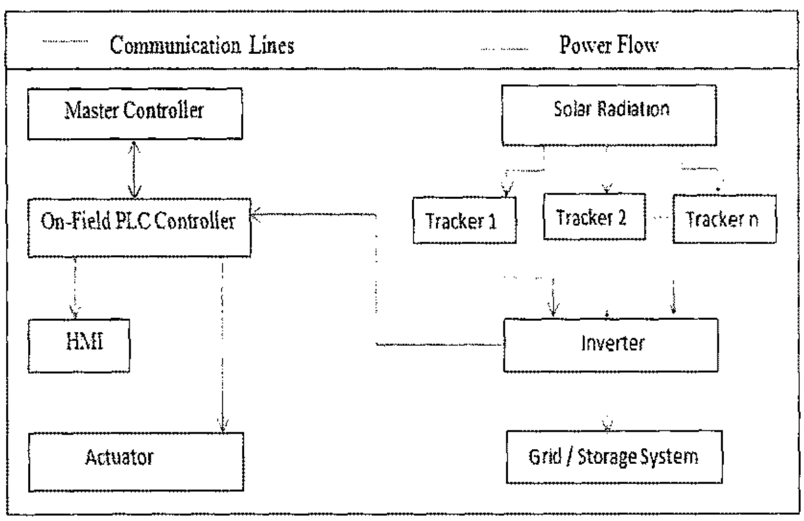

Fig 3.1 Block diagram of a solar tracking system

A solar tracker consists of an array of solar panels or modules which are connected in series and parallel to obtain higher currents and higher voltages. Typically for large scale power generation, solar trackers are designed to obtain a rated output voltage in between the range of 240V and 480V at an average current output of 12 A. A single solar tracker can produce an output power as high as 10KWh. The solar modules are mounted on solar panel mounting brackets which are designed to carry heavy loads. These brackets are supported with the help of metal rods which are generally mounted on the ground with either a concrete base or metal beams, designed to be used in any terrain. An illustration of a solar tracker is given in Fig 3.2.

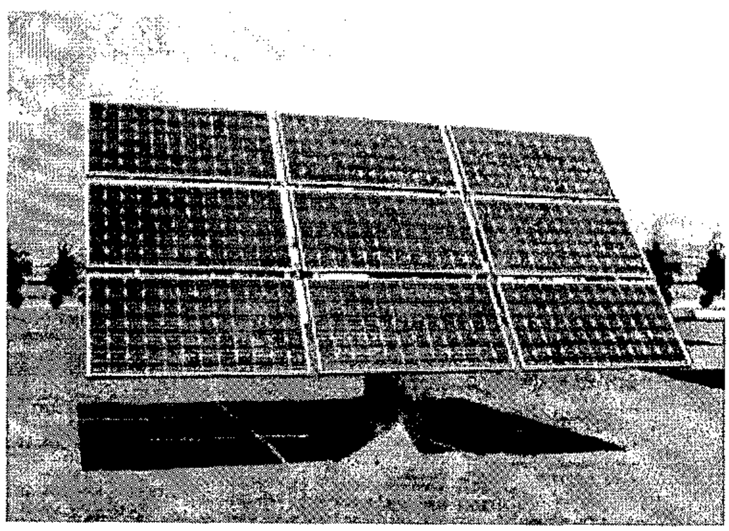

Fig 3.2 Solar tracker

An actuator is used to provide the required movement for the tracker during the day. It is connected to the mounting frame at a pre-determined location. Factors such as the length, speed and push and pull load capacity determine the location and position of the ends of the actuator. They are powered with the help of a DC power source. Actuators receive the control commands from the on-field controller. Communication between them uses either Modbus or Profibus communication. It is primarily a master-slave type of communication where the controller is the master and the actuator acts as the slave. Here the master provides the instructions to the slave and the slave follows them, but there is no acknowledgement sent back to the master from the slave. A Siemens S7-1200 PLC, which is typically used for solar tracking applications, can drive as many as 14 different slaves connected in a daisy chain.

Solar modules installed on the mounting frame start delivering the power based on the incident solar irradiance on them at a given point during the day. The maximum output power from the solar tracker is primarily based on two factors: the incident solar irradiance on the surface area of the modules and the output conversion efficiency of the modules itself. The movement of the tracker is to be programmed in such a way that the surface area of the solar tracker is always normal to the sun, which helps it in receiving maximum solar irradiance. The on-field controller takes care of the actuator to perform this task.

The on-field controllers are provided with the GPS for the very first time during the setup. The GPS is used to locate the position of the on-field controller and the trackers. The GPS is used to determine the latitude and longitude coordinates of the on-field controller. In Azimuth-Altitude dual axis tracking systems, the GPS is used to find the azimuth and altitude of the location. GPS is used to develop a layout of the on-field controllers accordingly using the master controller.

An algorithm which has been developed earlier is downloaded in the controller to obtain and store the latitude and longitude positions. The communication part of the program helps establish sync between the GPS and the controller. This part of the program has a communication head which establishes the required link and helps in sending and receiving the data from the GPS to the controller during the initial setup. There are various other blocks such as the data block, receive block and send block which receive and transmit data.

Although obtaining the data from the GPS and sending that to the controller is important, it is vital to maintain proper time sync between the two initially. A separate block known as the time synchronization block takes care of this task. This block verifies the system time and the GPS time by developing a time simulation to maintain sync between the two. This time synchronization block has multiple counters which record the time of the day and also help in differentiating day and night. Once the day folds up, the tracker is brought back to a safe position wherein the tracker is parallel to the ground. A separate block takes care of this task. Apart from these the controllers are also programmed to track storm-like conditions with the help of a wind sensor. A safe wind speed is determined for the tracker to stay intact instead of being ripped off due to the force, based on the tracker's weight.

The DC output power from different trackers is now sent to an inverter where it is converted into AC output power. The output from the inverter is fed into the grid. The capacity of the inverter determines the maximum number of trackers which can be connected to it. The inverter calculates the total AC output power and relays that information to the on-field controller which in turn forwards that to the Master controller located in the control room.

3.2 Motivation

In the above mentioned solar tracking system the amount of power generated by the solar trackers is monitored by the inverters only. Inverters have very high capacities which go as high as 500 KW to 1MW. The amount of power generated is only evaluated and monitored by the inverters. These inverters have peak conversion efficiencies as high as 98% for the 50 Hz system and 97.5% for the 60 Hz system. Typically, this value ranges from 95-98% [11, 16 and 17]. If a problem occurs, with the inverter, it could decrease the overall output power and this indirectly could increase the cost of the system. The overall increase in cost due to inverter failures depends on factors such as the inverter configuration, its reliability characteristics and the repair time [16, 17]. Moreover, the performance levels of the inverters decrease over time which adversely affects the overall conversion efficiency.

Nowadays, the inverters are designed to provide information such as input power and output power. Every inverter is supplied with DC power input from many solar trackers at a time. The number of trackers connected to the inverter depends on their configuration and capacity. All the data acquired from the inverter are sent to the on-field controller which keeps track of the inverter's performance characteristics. The data from all the individual inverters are acquired by the master controller. A detailed study of the data helps in determining the average value of the output based on various possible conditions.

3.3 Problem Statement

If there emerges a situation where the value of a certain inverter decreases when compared to the nominal value, it then becomes really difficult to detect the source of the problem. Factors such as weather, a malfunction in the inverter or a defect in the solar tracker might be the primary cause. The problem with the inverter can be taken for granted if the input to output conversion efficiency is less when compared to the standard value. Weather as a problem can also be determined easily, but, if the total input to the inverter itself is less compared to the average, then it becomes difficult to determine the faulty tracker. So, in order to determine the root cause of the reduction in output each and every tracker should be monitored.

Let us consider a situation where we have a 1 MW inverter and solar trackers each having a capacity of 10 KW. Therefore, in the above case there are 100 trackers whose combined output power is given to one single inverter. In such a situation it becomes really difficult to locate the root cause of problem and consumes a lot of human hours.

A good solution for the above mentioned problem is to use a micro-inverter system with lower capacities which handle inputs from fewer trackers. The cost of a 1MW inverter is approximately $250,000, and replacing this with 100 micro-inverters, each having a 10KW capacity will cost approximately $ 300,000. Use of a micro-inverter system would increase the total cost by almost 20%.

We have therefore proposed and developed a solution for the above problem which is cost effective and easy to use. We built a fault detection system which monitors the variations in the current and voltage of each individual tracker and relays that to the on-field controller. This system can monitor the above mentioned parameters of 14 different solar trackers using one PLC. Furthermore, this system helps in comparing the performance levels of the inverter which has the input of the combined trackers, with that of a single tracker. The data provided by this system can also help in making a detailed analysis of the decreasing efficiency over a period a time. A block diagram of the solar tracking system with our fault detection system included in it is shown in Fig 3.3

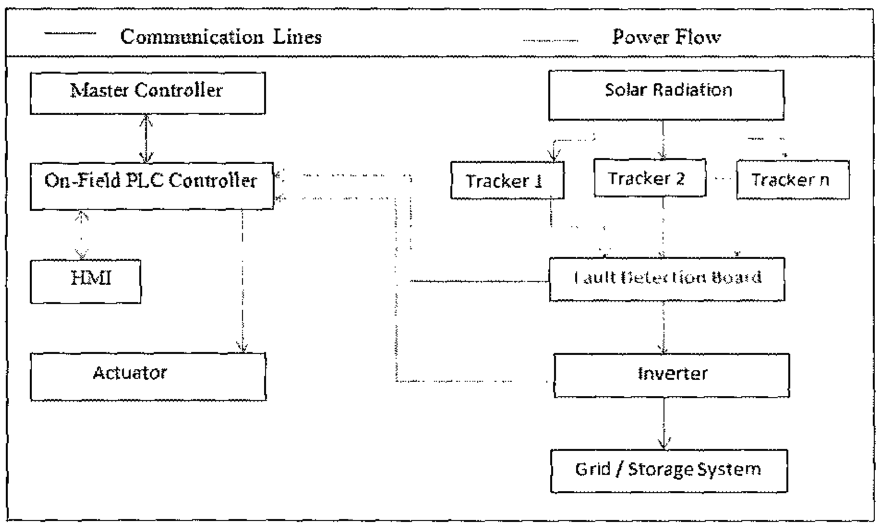

Fig 3.3 Block diagram of solar tracking system with the fault detection system

3.4 Overview of our system

The main objective of our project was to design a fault detection system which can measure the current for every individual solar tracker and relay that information back to the on-field PLC. The fault detection system (Fig 3.3) consists of 4 major components. They are:

1) Voltage regulator and power supply,

2) Sensor Unit,

3) Multiplexing unit,

4) PLC.

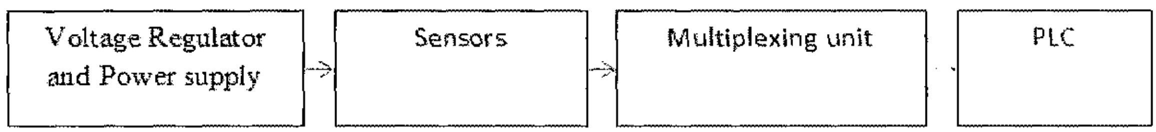

Fig 3.4 Overview of our system

CHAPTER 4

DESIGN AND FABRICATION OF THE CIRCUIT BOARD

Before starting construction of the hardware and software architecture, we defined the specifications of the desired board in terms of cost, size, functionality, ease of user interface and simplicity in design. The size of the board was an important aspect of this project as there are only a few companies which have developed applications with a few similarities to our project. We decided to build a board which is easy to carry, light weight and simple. The next important aspect to be considered was cost. The components are to be selected such that they are economical and can be easily implemented in the board without additional circuitry. Based on the above mentioned specifications, we have divided the project into 5 sections. They are:

1) Designing the Schematic,
2) Designing the Printed Circuit Board (PCB),
3) Assembling the Circuit Board,
4) Writing the PLC program to acquire sensor data,
5) Testing the board.

4.1 Drawing the schematic

The schematic of the fault detection system is sub divided into 4 different sections. They are:

1) Sensor Unit,
2) Power supply Unit,

3) Multiplexer Unit,

4) Interface between the board and the PLC.

4.1.1 Sensor Unit

This is the major section of the board. A sensor should be selected in such a way that it could take current as input and provide an output voltage proportional to the current. This output voltage would then be sent to the input channels of the multiplexer. Various parameters are to be considered while selecting the sensor. Parameters such as the input power supply, the maximum current range, the maximum isolation voltage value, the ability to measure current in both directions and sensitivity play a very important role in determining the performance levels of the board.

As mentioned earlier in chapter 3, in solar power generation the maximum power output of each tracker goes as high as 5 KW to 10 KW. In most power generation fields the output is directly fed into the grid, so the trackers are generally designed to deliver high voltages ranging in between 240V DC and 480V DC with an average current output between 10A to 15A under normal conditions. The selected sensor should definitely be able to take such high voltages and currents.

For our project, we have chosen a sensor which is a thermally enhanced, fully integrated, hall effect-based linear current sensor IC. The important characteristics of this sensor are: it can take very high basic isolation voltage with a peak value of 990V DC, it can measure input currents up to 50A AC or DC in both directions, it has a very low internal conduction resistance with a value of 100μΩ and it requires only a supply voltage ranging from 3 V to 5.5 V. For our application, the sensor related circuit is designed as shown in Fig 4.1.

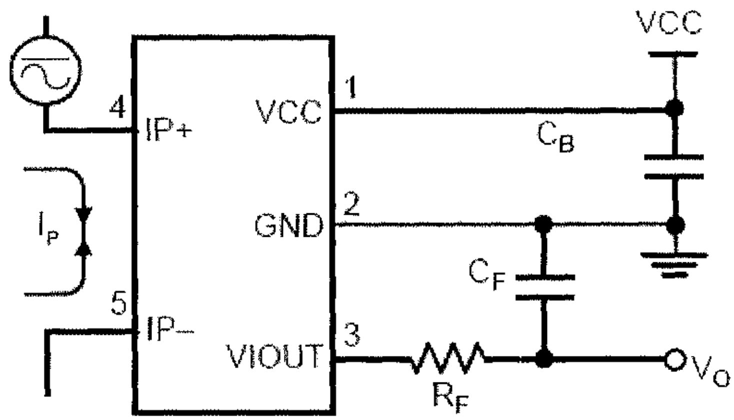

Fig 4.1 Circuit diagram of the sensor unit in our board.

Pins 1 to 5 are used for the device's input power supply, ground, analog output voltage, input terminal for current being sampled and output terminal for the sampled current respectively. The sensor consists of a precision, low-effect linear Hall circuit with a copper conduction path located close to the die. When a current is applied to the sensor through the copper conduction path, it generates a magnetic field which the Hall circuit converts into a proportional analog voltage. Since it has a very low internal resistance, the output power loss is kept low.

The input to the sensors is fed through connectors which are positioned at the ends of terminals 4 and 5. The connector selected can take currents up to 65 A. The value of the output load capacitance is chosen to be 10nF for better noise reduction, and the output load resistance is chosen to be 4.7 kΩ. These sensors are manufactured for a maximum efficiency at a bias voltage of 5 V and draw currents up to 13 mA. The sensitivity of the sensor is 60mV/A. The board consists of 14 such sensor units to measure current for 14 different trackers. The output voltage reading associated with each sensor is sent to one of the input channels of the multiplexer.

A voltage divider circuit is used to monitor the voltage levels of the solar trackers. All the sensors have a common node, and the voltage divider circuit is placed parallel to the sensors. The output terminals of the sensors are connected with the voltage divider circuit. 10 MΩ and 100 KΩ resistors are used to build this circuit. They reduce the value of the input by a factor of 1/101. The above values are selected to maintain the output voltage value under the 5 V range. The output of the voltage divider circuit is connected to the input channels of the multiplexer.

Prior to using the sensors in the circuit board, we tested the performance characteristics of the sensor.

4.1.2 Power supply unit

There are 14 different sensors which require a bias voltage of 5 V and draw a certain amount of current. Apart from the sensors we do need a power supply for the multiplexer. In order to provide an uninterrupted power supply, we need to choose a voltage regulator that delivers a constant voltage and has a higher current range. In our application, all the devices when taken into consideration require 5 V input voltage at an average current of 10mA. In order to provide power to all the devices we have chosen a voltage regulator which is a three terminal positive output voltage regulator which gives a constant output of 5 V DC and can deliver a current up to 1 A. It can take any input voltage ranging from 6.6 V to 30 V. For our application, we have a 24 V DC constant input voltage to the voltage regulator coming from the DC power supply present in the control box of the solar tracking system. This voltage is regulated to a 5V constant output from the voltage regulator. A lot of power is dissipated in the form of heat. A heat sink suitable for this regulator has been selected and attached to it. The circuitry associated with the voltage regulation and power supply is shown below in Fig 4.2.

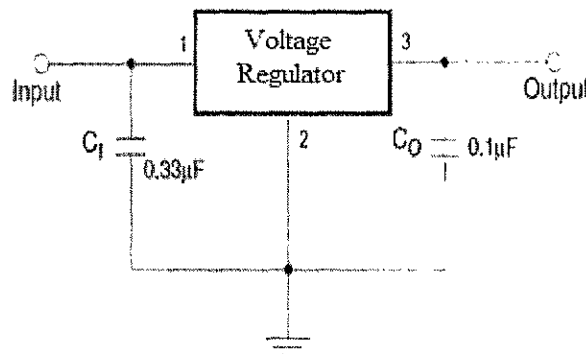

Fig 4.2 Circuit diagram for the voltage regulator unit.

4.1.3 Multiplexer Unit

In order to obtain the voltage values of the sensor's output at the controller, we used a multiplexer for selecting the desired output. We have 15 different values which are to be monitored. Hence, we have opted to use a 16:1 multiplexer which is a high-speed CMOS logic 16-channel analog multiplexer which can take 16 different input signals and read out the selected input signal into a single line. A 16:1 multiplexer has 4 select lines namelyS_0,S_1,S_2 and S_3 which are used to select an input channel. This is the data hub of our board. The pin out diagram of the multiplexer is shown in Fig 4.3.

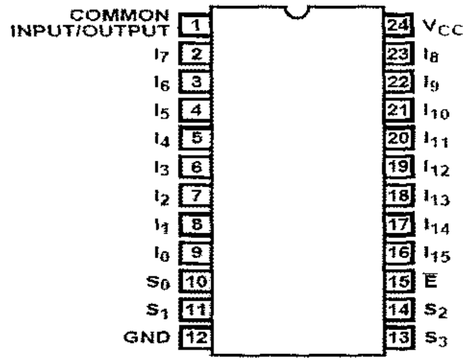

Fig 4.3 Pin out diagram of the multiplexer

The inputs from the sensor to the multiplexer are applied to channels I_0 throughI_{13}. The output from the voltage divider circuit is given to input channelI_{14}. The required input is selected with the help of the select lines. The truth table for four different select lines is used to select the required input channel. The select lines are either set to a low state (0) or high state (1) where they are supplied with either 0 V or 5 V respectively. The required voltage (5 V) is supplied with the help of the power supply from the board directed through the controller. The required channel number is set with the help of the PLC.

4.1.4 Interface between the board and PLC

Two separate connectors are used to connect the fault detection board with the power supply line and the PLC. The first connector is used to connect the 24 V DC power supply to the voltage regulator. The second connector is used to provide a connection for the select lines, reference voltage for the controller and the connection between the analog inputs of the controller to the multiplexer.

4.2 Designing the Printed Circuit Board (PCB)

This section will describe the practical implementation of the board design. It is divided into two stages: 1) designing the schematic and 2) designing the PCB.

4.2.1 Prototype and Designing the Schematic

The first step in building the fault detection board was to create a complete schematic design, which includes all the components and their internal connections in the circuit. We have used the free version of the *PCB Artist* software provided by Advanced Circuits. Before making the full-fledged schematic design, we first tested the components to be used. For this, we created a prototype by using a demo board consisting of the sensor and the required load capacitors and resistor along with other components being used for the final board. After fixing the power connections and connecting all the components, the prototype was tested to be operational. After this, the schematic was drawn using the software (PCB Artist). An illustration of the schematic is shown in Fig 4.4.

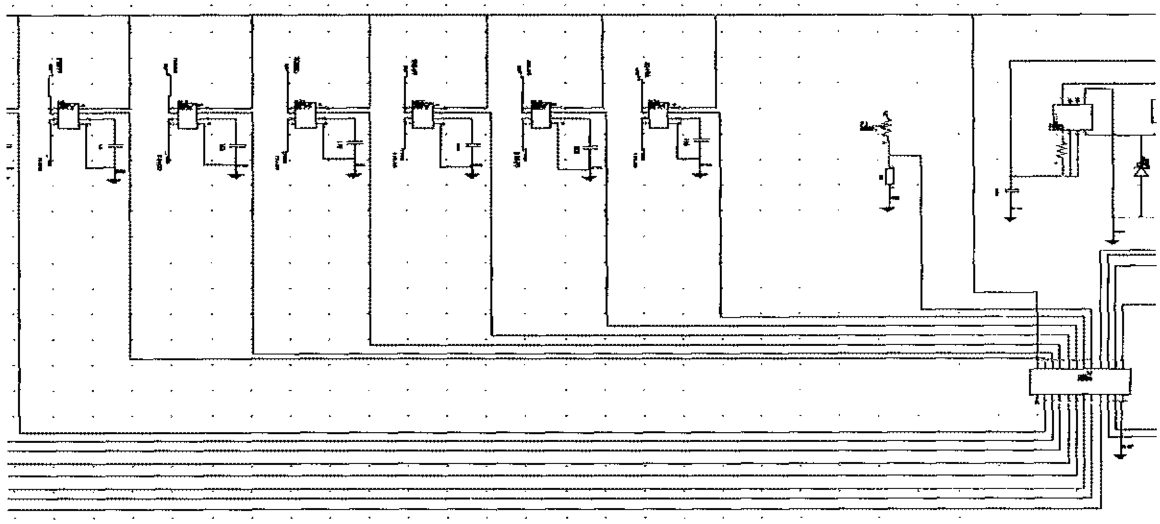

Fig 4.4 Part of the schematic design for the board

4.2.2 Designing the PCB

Once the schematic design was verified, we started working on the PCB version of the board. The major part involved in this process was finding the exact components (related to the board) that would perform the desired functionality and then creating the schematic symbols along with the PCB symbols for the components for the board design. PCB Artist provides a large library manager for components, but many of the components used in our board had different dimensions or were not available. Therefore, for each component not found in the library we had to analyze the components datasheet, create a schematic symbol and then create a PCB symbol by using the exact dimensions obtained from the datasheet, otherwise the components would not fit in the board. An illustration of this process is shown in Fig 4.5. All the components used in this design are through-hole.

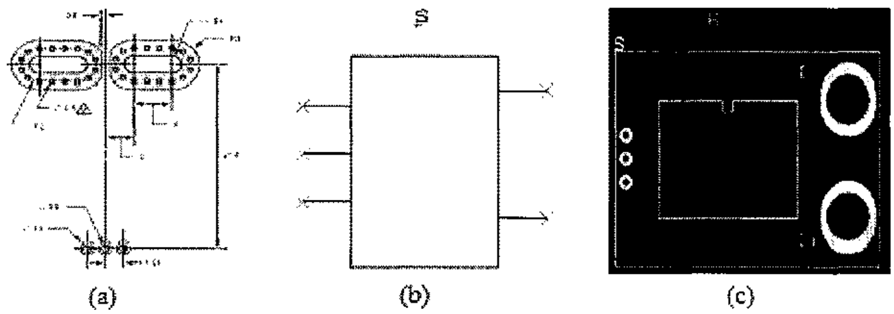

Fig 4.5 Process showing component symbol design in PCB Artist: (a) obtain dimensions from datasheet, (b) create a schematic symbol and (c) create the PCB symbol.

Once all the components have been designed, they are saved in the library manager. After this, the software provides an option for us to automatically convert the schematic into a PCB layout design. For this we have to set the dimensions of the board. We opted to use a 2 layered standard board with material substrate and thickness being *FR4* and *0.062 inches* respectively. The copper weight is chosen to be *2 Oz per square foot*. Once the schematic is translated into the PCB design, we can allow the tracks to be auto routed using the *auto router* option or do it manually. However, in designs involving complex designs, the auto router performs inconsistent routing. Thus, we routed all the tracks manually. All common-practice rules such as the minimum trace space and trace width are followed. Since very high currents will be passing through the sensor and the board, the trace width associated with the input and output terminals of the sensor and the connectors have to be increased to a safe value. The trace width has to be calculated by using the industrial guidelines for trace widths. The formula used to calculate the cross-sectional area of the trace for external traces is,

$$I = 0.048 * dT^{0.44} * A^{0.725} \qquad (5.1)$$

where I is the current, dT is the temperature rise above ambient in Celsius and A is the cross sectional area. We have calculated the trace width considering the fact that the sensor is rated to measure a maximum current of 50 A. Based on the above equation, the trace width should have a minimum value of 900 *mil* and a minimum cross sectional area of 2500 mil^2 at 25 $°C$. Factors such as peak voltage, copper thickness and temperature changes have also been considered. A copper pour area is used to provide the trace width between the sensor and the connector. An illustration of the final PCB design is shown in Fig 4.6. The traces associated with the top layer and bottom layer are marked in red and blue respectively.

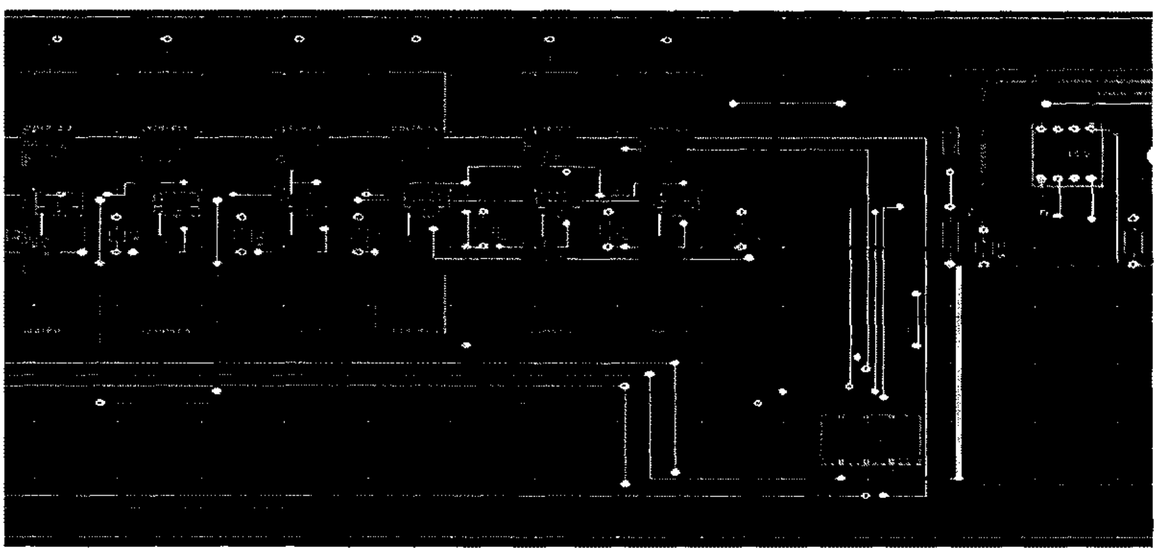

Fig 4.6 Part of the final PCB design

The next step was to manufacture the PCB design. There are many companies that can produce PCBs, but we opted to go with *Advanced Circuits*, which provided the PCB Artist software.

4.2.3 Initial Design

In the initial design of the board, the majority of the components were surface mounts. All sensors, resistors, multiplexer, voltage regulator and connectors were surface mounts. The power supply circuit used was the ADP 1111 *IC*. In order to provide a stable output voltage, we had to use additional circuitry which increased the number of components and the cost indirectly. Moreover, the soldering of surface mount components consumes a lot of human hours which increases the overall cost of the board.

While testing the board, it was found that there was a considerable voltage drop due to the heating of the *IC*. Therefore, this power supply circuit was replaced in the new design with a voltage regulator circuit which has a heat sink attached to it to dissipate the heat. It was also observed that the connectors used to supply current to the sensors, are easily torn out if there is force applied in the vertical direction.

4.3 Assembly

The final step in the process of completing the board is soldering the components. Since, all the components are through hole, it has been completed in a short span of time. There was a problem while soldering the sensors, however. The pad holes for pins 4 and 5 were slightly smaller compared to the required dimensions. This problem was rectified by trimming a small portion of the leads of the sensors. The finished board looks as shown in Fig 4.7.

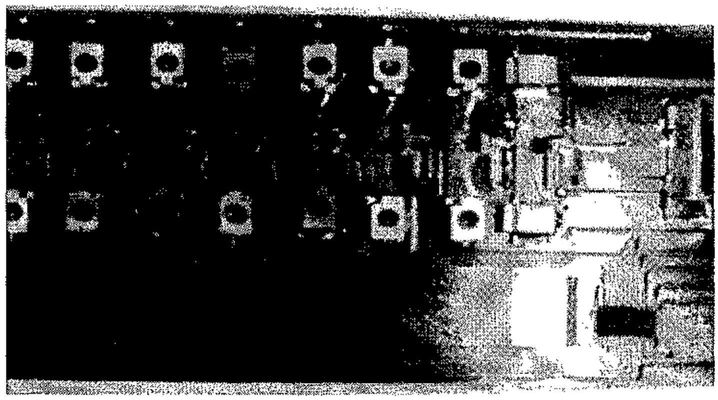

Fig 4.8 Part of the fabricated circuit board.

4.4 Cost Analysis

All the components have been selected in such a way that the overall price of the board is kept low without compromising functionality. A cost comparison for 1 board (our board) and manufacturing on a large scale (5000 units) is given in Table 4.1.

Table 4.1 Cost comparison for manufacturing single board versus large scale manufacturing.

Component Name	**1 board (in $)**	**5000 Boards(in $)**
PCB Board	114	28
Sensors	98	49

Component Name	**1 board (in $)**	**5000 Boards(in $)**
Multiplexer	1.33	0.46
Resistors	2.7	0.70
Capacitors	1.1	0.33
Voltage Regulator	0.67	0.20
Heat Sink	2.48	2.17
Connectors	3.10	2.00
Assembly	-	76.16
Total (in $)	***223.38/board***	***159.02/board***

The assembly cost includes the cost of labor for assembling the circuit board. The total price of the board after fabrication and labor charges would sum up to $159, when produced on a large scale.

4.5 PLC Programming

This section describes the software program used to acquire the data from the PCB. The software used is *Totally Integrated Automation Portal (TIA)* provided by Siemens. The controller used is a Simatic S-7 1200, which has 14 inputs, 2 analog input and 10 output slots. The main tasks when it comes to the software part of the project are to obtain the data from the multiplexer using the analog inputs of the controller, write a program to control the select lines and display the output.

4.5.1 Devices and Networks

This is the first step in writing the program. We have a list of many different PLCs present in the software. We should select the exact PLC being used for our application and various other modules being used. All the required operational parameters, such as configuring the Internet Protocol (IP) Address for the CPU and local outputs of the CPU, are done. Time zone and local time are set in the program.

4.5.2 PLC Program

Based on our requirement we have divided the program into 3 separate blocks. They are the Main block, multiplexer control block and the analog data read block. The Main block is represented in the OB1 (Organization Block) and controls the execution of the user program. Specific events in the controller trigger the execution of an organization block. The cyclic OB contains the main program. All the Function Blocks (FB) and Functions (FC) are called by the main block while executing the program.

We have used a separate block for implementing the *multiplexer control* using the Function (FC). This block is executed when called from OB1. The main reason to use a FC for this program is to reduce the usage of global memory variables of the controller. FC uses local memory variables. A flow chart is shown to better explain the functioning of this block in Fig 4.8.

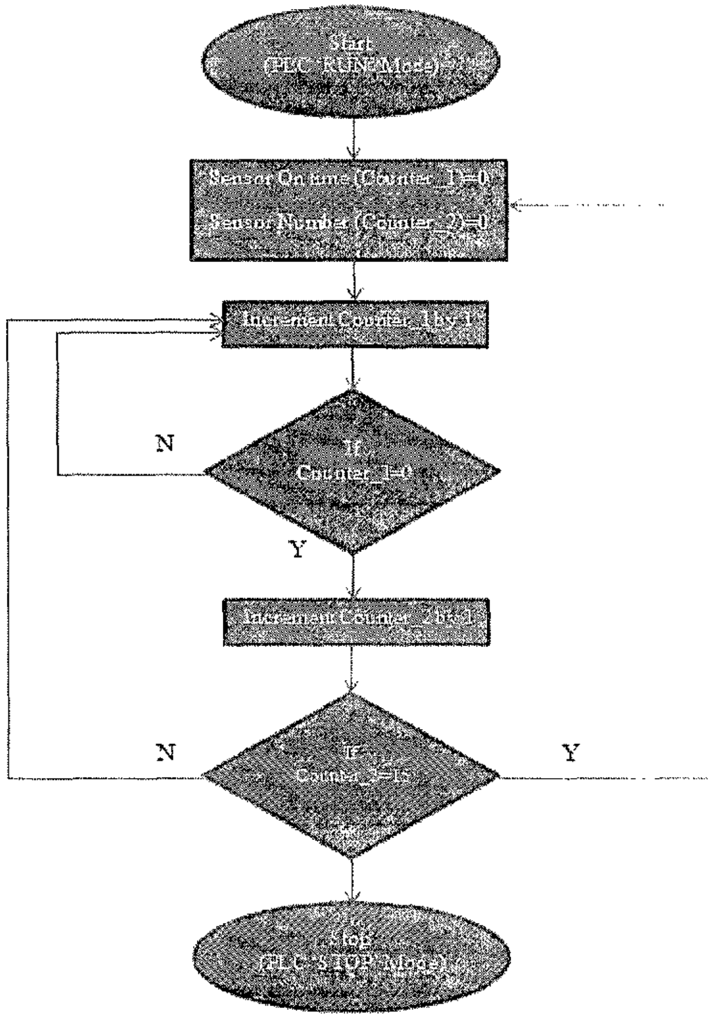

Fig 4.8 Flow chart for the multiplexer control

We have 14 different sensor outputs which are to be selected one after another. We have given a specific 'ON' time for each multiplexer output. After all the 14 outputs from their respective sensors are selected, the program redirects the controller to start from the first output. A positive pulse with a clock frequency of 1Hz is used to trigger the program. Data is acquired at the very first moment the program takes in the analog value of the multiplexer output. Since the select lines use the *Boolean* notation, we have to give a set of 0's and 1's in order to select a multiplexer output. Since there are 4 select lines, we require 4 output of the controller. For this purpose, we have used a *word* data type to select the outputs from *q0.0* to *q 0.3*. An image of the output slots is give below in Fig 4.9.

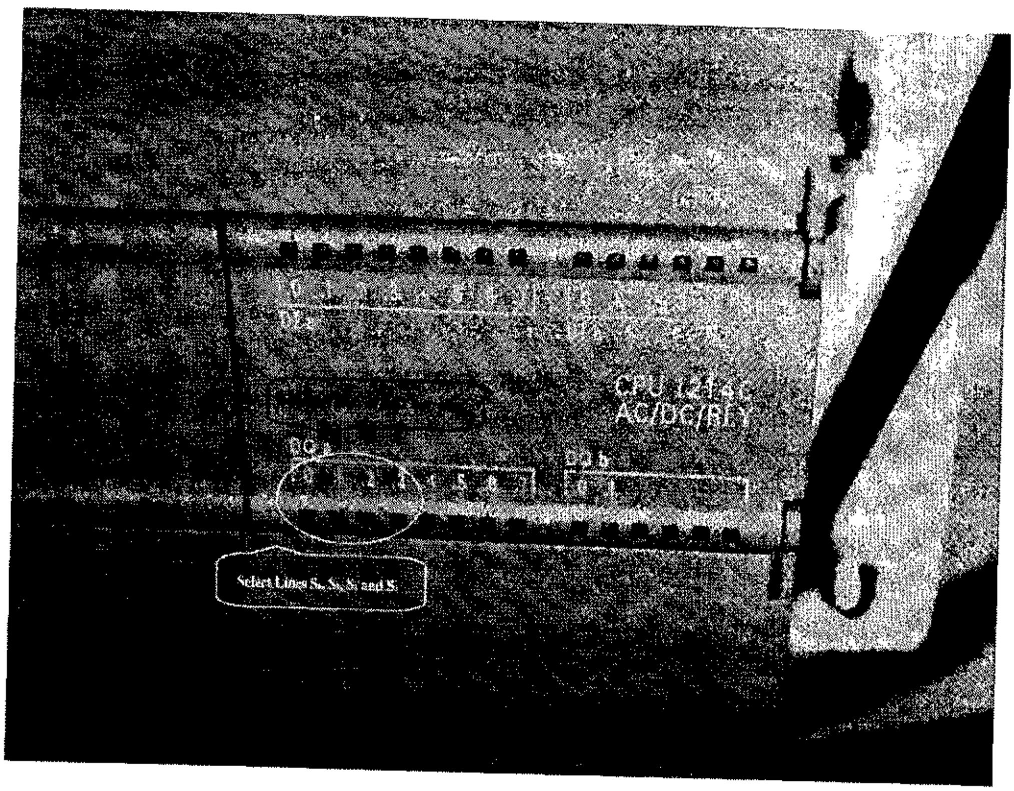

Fig 4.9 Output slots of the controller

We have used a memory word to select and store the output (output channel number from 0 to 15 of the multiplexer). In TIA, the least significant bit of a *word* starts from the right. We have later changed our program accordingly.

In order to acquire the data from the multiplexer, we have used a FB (Analog Data Read) as these have important data that will be used globally. We used Functional Block Diagram (FBD) programming language for this part to make our work easier. The data from the multiplexer is acquired by this block. That acquired data is then scaled down and normalized to a value between 0 and 10. Based on the normalized value we calculate the current.

The FB and FC are then dragged into OB1. The final program was compiled and checked for errors. Once it was error free, we downloaded the program into the controller.

CHAPTER 5

TESTING AND ANALYSIS OF THE CIRCUIT BOARD

In this chapter, we evaluate the project in terms of the board's performance, software program and its overall functionality. The various measurements and analysis are presented.

We used a few instruments to create an experimental setup in order to test the board. A 24 VDC power supply was needed to supply power to the board, a small resistive load was required to draw currents and a high power DC power supply was required to provide high currents. A couple of digital multi meters were required to measure the voltage and current readings.

5.1 Experimental Set Up

Prior to testing the board we have tested the characteristics of the sensors. The V-I characteristics of the sensor are shown in Fig 5.1 which shows a linear relationship, and the measurements are in agreement with the manufacturer's data sheet. Table 5.1 shows the current and voltage reading for 3 different sensors.

Table 5.1 V-I Characteristics reading for 3 different sensors.

Sensor-1		Sensor-2		Sensor-3	
Current	Voltage	Current	voltage	current	voltage
0	0.59	0	0.59	0	0.6
0.43	0.61	0.27	0.6	0.46	0.61
0.806	0.63	0.632	0.62	0.957	0.65
1.07	0.65	0.992	0.65	1.82	0.69
1.78	0.69	1.63	0.68	2.2	0.72

Current	Voltage	Current	Voltage	Current	Voltage
1.93	0.7	2.03	0.71	2.5	0.74
2.096	0.71	3.068	0.77	2.8	0.75
2.4	0.73	3.67	0.81	3	0.77
2.7	0.75	4.2	0.84	3.91	0.83
3	0.77			4	0.83
3.5	0.8				
4	0.83				

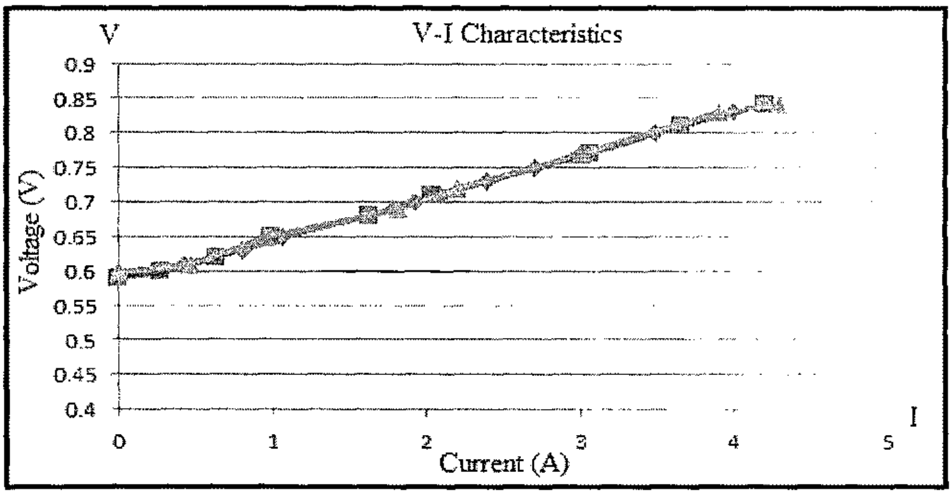

Fig 5.1 V-I Characteristics of the sensors

A 24 V DC power supply is connected to the input terminals of the voltage regulator. Two wires are connected from the output terminal of the multiplexer and ground to the analog inputs of the PLC. Similarly, a wire is drawn from the 5 V terminal of the output connector to the reference voltage slot of the PLC. Next, the 4 select linesS_0,S_1,S_2 and S_3 are connected to the outputs of the PLC from q0.0 through q0.3 respectively. We have to make sure that the wiring is correct and the board is properly grounded. A schematic for the connections is shown in Fig 5.2.

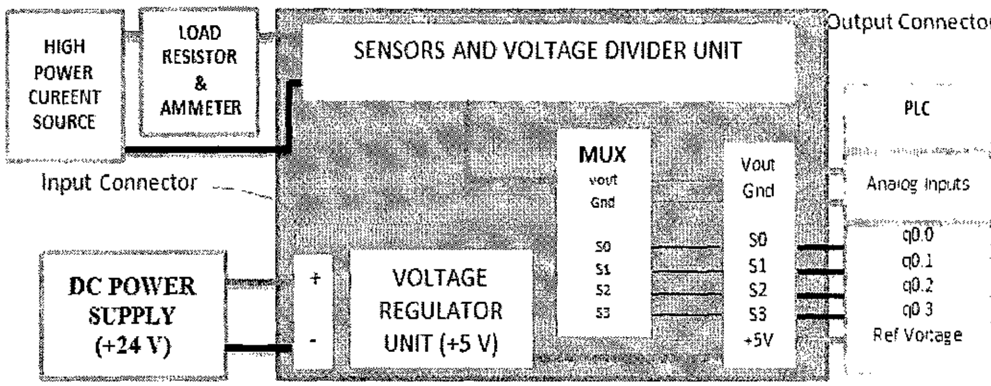

Fig 5.2 Schematic for the connection

Prior to testing all the functionality, we had to test the board with high currents. We used a programmable DC power supply which was able to provide power up to 12,000 watts. This device could deliver currents up to 600 A at 20 V.

For current to pass through the sensor, we need to provide a certain load which should be able to carry high current. Initially, we used a 1 Ω resistor rated up to 100 watts but this was not able to sustain high current. It rapidly heated up and ultimately burnt out. In order to supply high currents, we built a resistor circuit which consists of 3 resistors, a 1 Ω resistor and two 0.5 Ω resistors, all parallel to each other. A circuit diagram for this arrangement has been shown in the Fig 5.3.

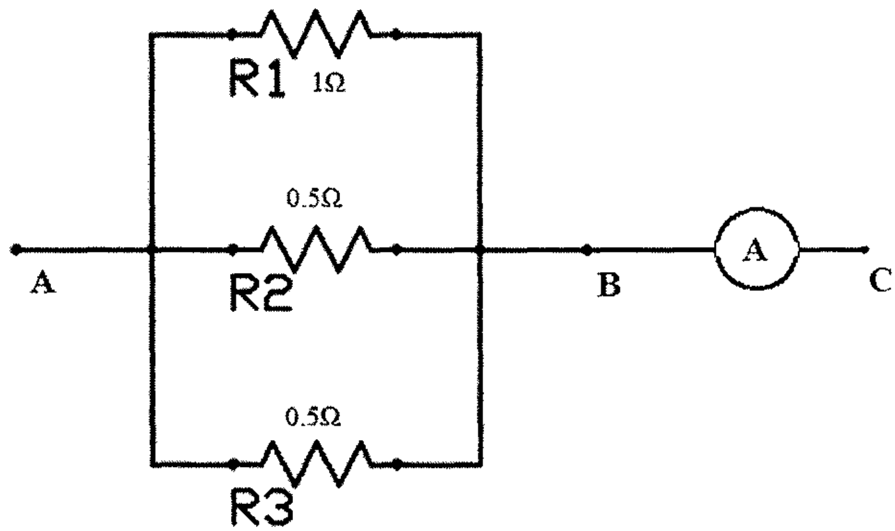

Fig 5.3 Circuit diagram for load resistors and ammeter connection

The resultant resistance was 0.2 Ω. To avoid heating up the resistors, we attached a heat sink to all of them. This resistive load was connected in series with the sensors. We finished the circuit by connecting the sensor 7 in series with the resistors and the DC power supply.

5.2 Measurements and Analysis

We did a final check on all the wiring. Next, the 24V DC was turned on. The output of the voltage regulator was checked and tested to be 5V DC, and it was supplying a current of 157 mA to all the components in the board. The high power DC power supply was switched ON. It was digitally programmed to supply 10A at 2V. Next, the controller was set to the RUN mode. All the channels of the multiplexer were observed to be switched ON for 5 seconds as written in the program, and data was acquired from each and every channel. Every 5 seconds, the channel number was increased by 1, and after they reached 15 it was sent back to channel 0. An illustration of the controller while the programming was running is shown in Fig 5.4.

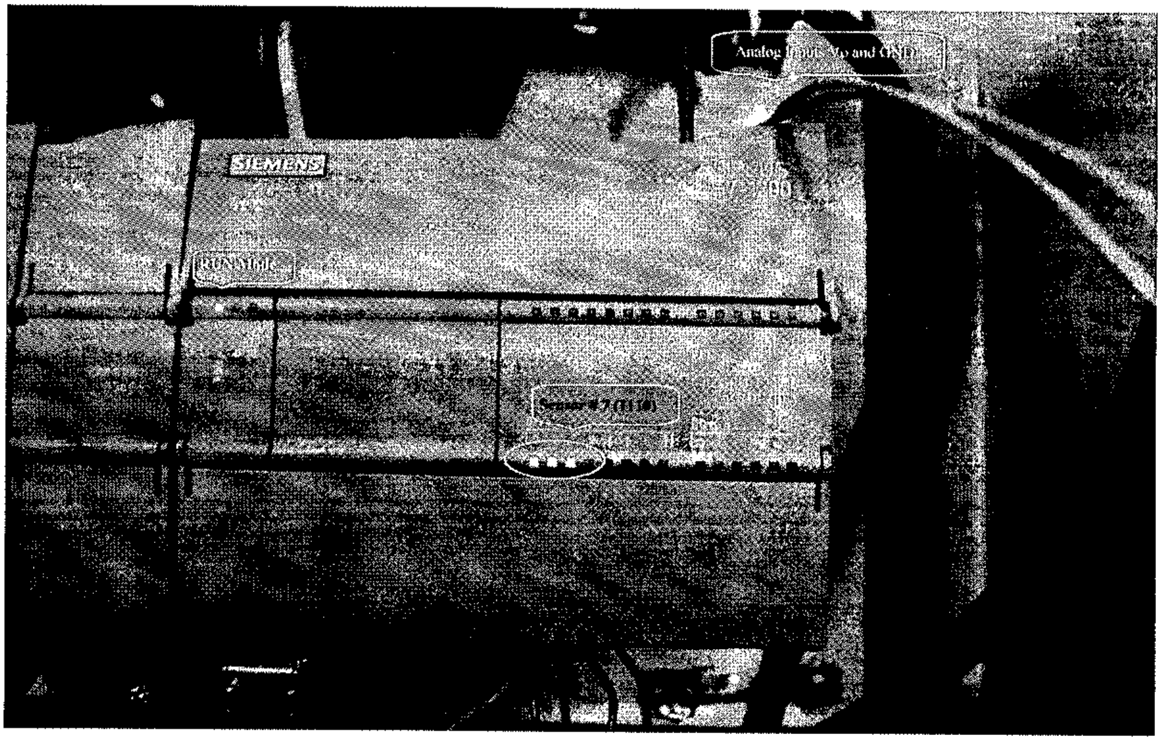

Fig 5.4 Controller while our PLC program was running

The acquired data can be viewed in the program itself. We used the monitor option provided by the software to see the data associated with each tag used in the program.

Illustrations of all the results are shown in the figures below. Fig 5.5 illustrates the working of the multiplexer control using the controller. Clearly, it shows the selected sensor number to be 7.

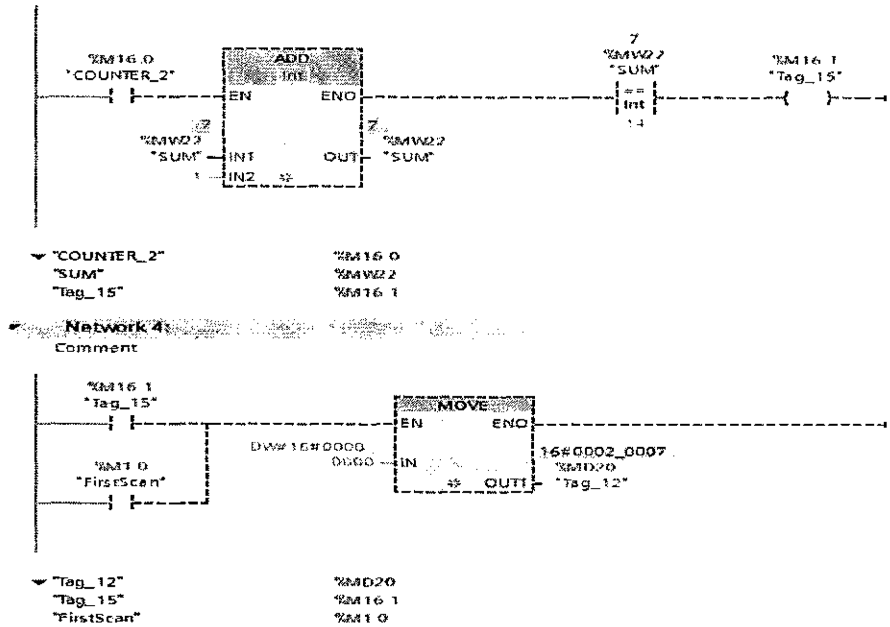

Fig 5.5 Working of the multiplexer control function

Analog data read block displays the scaled valued of the input obtained at the analog inputs of the controller along with the normalized value. A screenshot of the above function block has been shown in Fig 5.6.

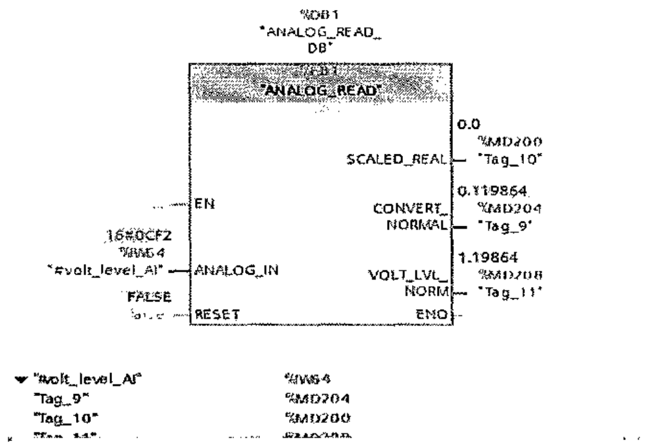

Fig 5.6 Working of the analog data read function block

Fig 5.7 shows the display of the final current reading obtained in the program. We set an input current of 10A and the displayed result is close to the set value.

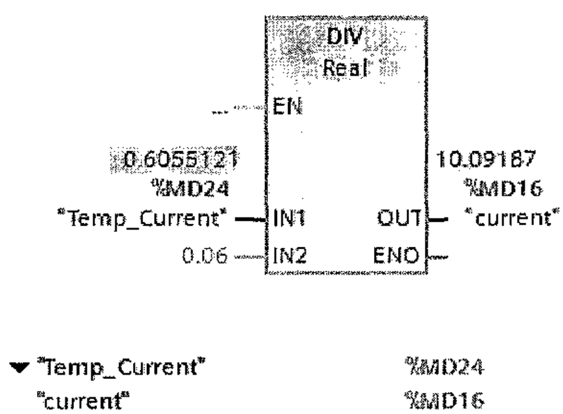

Fig 5.7 Display of the measured current

CHAPTER 6
CONCLUSIONS

Developing new sources of energy based on renewable energies is critical for the future of the world and our economy. Solar energy is a widespread source of energy readily available worldwide, every day. To harvest the maximum power from this source, however, requires developing new technologies, whether it be higher efficiency modules or PV tracking systems.

The advantage of a PV tracking system is that it can generate up to 30-60% more power than a fixed system and provide information on the health and maintenance required for the system via the programmable logic controller. One problem, though so far has been the capacity to measure precisely the output power of each tracker as opposed to the output of the inverter, which can handle up to 100 trackers.

We have therefore developed a new health monitoring system based on Hall Effect sensors connected to a multiplexer, controlled via a new program by a PLC. We have successfully demonstrated that both the current and the voltage of each single tracker can be measured in real time and provided to the user for analysis. We made sure that our design and the components that we used were both rugged and inexpensive.

The next generation of a health monitoring system to be developed will need to have the same qualities as the system we just fabricated but progress at the same time towards several directions, notably (i) reduced price; (ii) reduced size; and (iii) increased maximum time before failure.

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