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PHOTOVOLTAIC TRACKER OPTIMIZATION WITH UNIQUE FAULT DETECTION AND ENHANCED COMBINER SYSTEM

by

Caitlin Nicole Conway
B.S. May 2012, Salisbury University

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
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ABSTRACT

PHOTOVOLTAIC TRACKER OPTIMIZATION WITH UNIQUE FAULT DETECTION AND ENHANCED COMBINER SYSTEM

Caitlin Nicole Conway
Old Dominion University, 2013
Director: Dr. Sylvain Marsillac

Renewable energy resources are rapidly becoming extremely important as the world's energy consumption continues to rise. The most popular of these resources is solar energy and more specifically photovoltaic energy. Currently, solar modules on the market are still not highly efficient. In order to increase the productivity of solar energy systems, larger fixed-panel photovoltaic systems or tracking photovoltaic systems are utilized. The major disadvantage of larger photovoltaic systems is the increased space requirements. Therefore, tracking photovoltaic systems are the best alternative to achieve higher solar energy yields.

To date, the only method of monitoring tracking photovoltaic systems is with the aid of existing inverters. However, inverters account for approximately 50% of photovoltaic system faults making this technique highly unreliable. This method is also very broad in the level of monitoring, limiting the data to the combined power of all photovoltaic strings wired to the inverter. Therefore, small-scale faults within the system will go unnoticed and significantly reduce energy yield over time.

This thesis research proposes a solution to the poor fault detection monitoring systems available for photovoltaic tracker applications. The improved monitoring system developed is capable of monitoring tracking photovoltaic systems down to the individual string current level. The system is controlled with a Programmable Logic Controller and

monitors a maximum of sixteen photovoltaic strings. The system is also able to monitor the combined string voltage of the sixteen strings to aid in accurate power calculations. The unique feature of the developed monitoring system is the integration of the combiner system. This further utilizes the existing components of the systems and will greatly increase photovoltaic tracker productivity for many years to come.

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dedicated

to my parents Harold and Sarah Conway

for their undying love and support

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I would also like to express my gratitude to Dr. Shirsak Dhali and Dr. Oscar González. Dr. Dhali has continuously offered invaluable advice and guidance throughout my research. Dr. González has also been instrumental in guiding me through my career at Old Dominion University. I wish to thank them both for so kindly participating in my thesis committee.

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Most importantly, I would like to thank my family for their never-ending support throughout my educational endeavors. In particular, I wish to thank my parents. Without their love and support I would be lost.

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CHAPTER 1

INTRODUCTION

1.1 Background

Renewable energy sources are becoming extremely important as the world's energy consumption continues to grow each year. At the current rate of population growth and power consumption, the world will soon be unable to meet energy demands. Therefore, society must utilize renewable resources as a means of supplementing the necessary energy needs. Such renewable energy sources include wind, solar, biomass, geothermal, and hydropower. Although all of these sources hold great potential, one of the more rapidly advancing sources is solar. The sun is an extremely reliable and abundant resource, expected to exist billions of years into the future. This makes solar energy an ideal means of meeting the increased energy demands now and in the future.

There exist several types of solar energy which include photovoltaics, solar hot water, passive solar, and concentrating solar power. Photovoltaics is the conversion of solar radiation to electrical power and is one of the most popular types of solar energy. Solar hot water is also very popular and involves utilizing the sun's energy to heat water used within a household. Passive solar is often used in larger scale buildings by strategic window placement to reduce energy costs. Finally, concentrating solar power is used to convert solar energy into heat and is typically used in places where sunshine is abundant such as deserts. While all of these methods of utilizing the sun's energy are very effective, photovoltaics is becoming a highly sought means of cutting electricity costs.

This thesis focuses on the development of safer and more efficient methods of harnessing solar energy. One of the best methods of achieving these goals is close monitoring of the solar hardware. Proper detection of any faults in solar energy systems ensures the highest productivity as well as safety. This thesis seeks to shorten the time in which damaged or faulty solar energy systems are detected and restored. These essential improvements of photovoltaic devices will greatly improve and help propel the solar industry far into the future.

1.2 Thesis Organization

The goal of this thesis research is to develop a fault detection system which improves the efficiency of today's photovoltaic trackers, by reducing notably the operation and maintenance costs and increasing power generation. The need for a specialized photovoltaic tracker monitoring system has developed due to the inaccuracy and inefficiency of existing monitoring systems. Currently, photovoltaic monitoring systems rely on the inverters to provide current, voltage, and power output measurements. This method is unreliable as inverters account for a significant portion of faults within the photovoltaic systems. The inverters are also only capable of providing system information for the combined strings which makes identifying the source of a fault very difficult. The system developed in this thesis will monitor the individual string currents and combined voltage measurements of the photovoltaic tracker and alert when problems occur. These alerts will enable the user to immediately identify any faults which will affect the systems productivity. The instant information gratification will reduce the time required to restore the photovoltaic tracker systems to normal function.

This reduction in time will ensure increased productivity and overall return on investment.

Chapter 2 details photovoltaics, photovoltaic trackers, and the components integrated in the systems. This chapter aims to qualify the advantages of tracking photovoltaic systems as opposed to fixed photovoltaic systems.

Chapter 3 outlines monitoring systems for photovoltaic tracker applications. This chapter states the motivation behind this research as well as the problem statement. Chapter 3 also provides an overview of the monitoring system developed in this thesis.

Chapter 4 explains the numerous types of current sensors available on the market. This chapter explains the differences between the current sensors available and provides pertinent numerical data. This data is then compared and used to select the proper current sensor for the photovoltaic tracker monitoring application.

Chapter 5 details the design and fabrication of the photovoltaic tracker monitoring system. The methods of schematic and printed circuit board development are explained. Finally, the reasoning behind these design decisions are explained.

Chapter 6 explains the testing procedures used to analyze the photovoltaic tracker monitoring system. These procedures verify the validity of the monitoring system design.

Finally, Chapter 7 summarizes and concludes this thesis. This chapter also discusses future works and goals to further improve tracking photovoltaic systems.

CHAPTER 2

PHOTOVOLTAIC SYSTEMS

2.1 Photovoltaics

2.1.1 Introduction

Photovoltaics is the conversion of solar radiation to electrical power and is one of the most popular types of solar energy. All photovoltaic systems operate according to the same physics principles. These principles are referred to as the photovoltaic effect and involves the excitation of electrons by photons or light particles. When the electrons become excited they are transferred from the valence band to the conduction band. The photovoltaic effect utilizes a pn-junction to produce the electric current. This pn-junction contains an n-type semiconductor material atop a p-type semiconductor material. As sunlight hits the n-type and p-type layers, the semiconductor absorbs the photons and creates free electrons and holes. These carriers diffuse to the depletion region between the two semiconductor layers, where they drift to the other side. The free electrons then pass into an external load. As the free electrons recombine with the holes in the p-type layer (electron-hole recombination) electrical power is produced.

The electrical current resultant from photovoltaic devices is always in the form of direct current. There exist two types of current which include alternating current (AC) and direct current (DC). Alternating current is current which periodically changes the direction of flow. In contrast, direct current is current which only flows in one direction.

The DC power produced by solar cells can then be used in a variety of applications or switched to AC power.

2.1.2 Photovoltaic Power

The photovoltaic effect is applied in the industry with the use of a photovoltaic system. A typical photovoltaic system schematic is shown in Figure 2.1. Such systems are comprised of arrays of solar panels. Each solar panel contains numerous solar cells which convert the solar radiation into DC electric power. The solar panels are then connected in series to form "strings." The inverter used has a maximum voltage rating and thus limit the size of each string. The strings are then sent to a combiner box which converts all of the DC string currents into one large DC string current. Since most electrical applications require AC current, the DC current must be transformed into AC current. This operation is performed by an inverter. When the DC current arrives at the inverter the voltage can be as high as 600V or even 1000V in large behind-the-fence installations. After passing through the inverter, the voltage is reduced to 120V or 220V depending on the country of installation. The frequency of the current is also changed in the process since DC power has a frequency of 0Hz. The resultant AC current has a frequency of 60Hz or 50Hz again depending on the country of installation. The number of combiner boxes and inverters depends on the size of the solar field. Once the DC string has passed through the inverter, it is then ready to be connected to the main power grid. When tied to the grid, the solar produced power is non-dispatchable and must be used right away. However when stored in a battery, solar power is dispatchable and can be used as needed. In this case, the panel strings do not pass through an inverter and remain as DC power. This makes solar power very versatile and readily valid for a variety of applications.

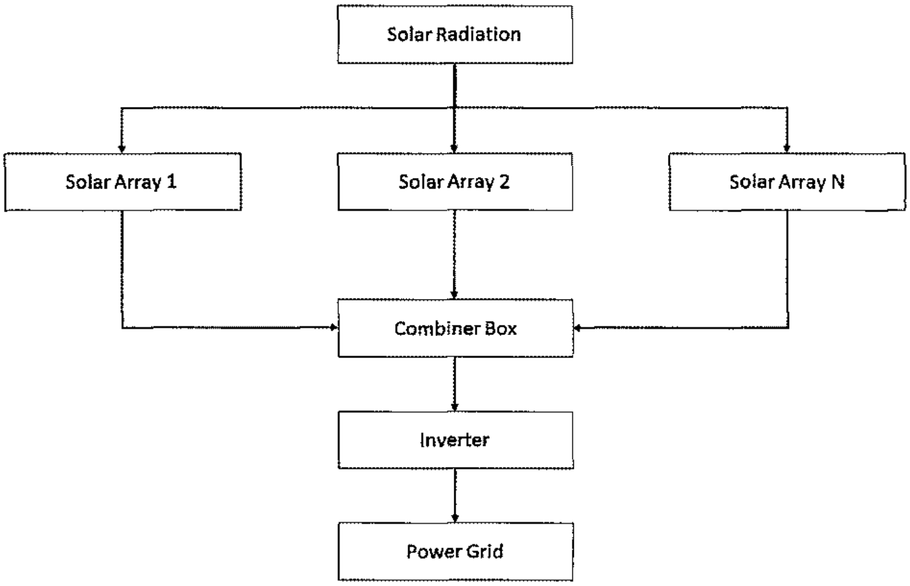


Figure 2.1 Photovoltaic System Schematic

2.1.3 Advantages of Photovoltaics

Photovoltaics is a very abundant and adaptable resource. One of the most prominent advantages of photovoltaics is the source of fuel. All photovoltaic devices rely on the sun to produce power. The sun is a very robust and reliable resource with a life expectancy of several billion years [2]. Solar energy is also widely obtainable as opposed to non-renewable sources which are unevenly distributed. Luckily, there exist no disputes over consumption of the sun's energy as the sun is a free resource. Photovoltaic energy has many other advantages including the lack of emissions in the environment. Solar panels release zero toxins during the production of solar energy. In contrast, fossil fuel sources of energy have high impacts of both extraction and consumption. This makes photovoltaic energy a green, renewable, and reliable source for meeting today's energy demands.

Another important advantage of photovoltaic systems is the low maintenance required. Unlike oil and coal refineries, solar energy maintenance is limited to cleaning of the panels and upkeep of the electrical equipment. Most solar energy systems have an expected lifetime of at least twenty years [2]. This far outweighs the expected five years for return on investment [2]. Beyond this time period, the only cost associated with photovoltaic systems is routine maintenance and minor repairs. Contributing to this investment return is the reduction in transmission of solar produced energy. Since many photovoltaic systems produce energy at the location of use, the costs associated with power transmission are decreased. Therefore, photovoltaics are not only green but also highly cost-effective.

Although the initial investment of a photovoltaic systems is high, the prices of the materials are rapidly reducing. This increased drop in cost is largely in part of the continued growth of the photovoltaic industry. As solar technology becomes more advanced, the cost of production is eventually reduced. Photovoltaics holds great promise and continues to progress in both efficiency and affordability. With further interest and investment, the photovoltaic industry will undoubtedly propel the world into a renewable energy rich future.

2.1.4 Disadvantages of Photovoltaics

Although photovoltaics have an abundance of advantages, there do exist several disadvantages. The most prominent disadvantage of photovoltaics is the high cost of investment. While photovoltaic systems are very beneficial, the initial cost of investment is currently very expensive. Contributing to this high cost is the amount of space required to install a photovoltaic system. Many oil and coal refineries only occupy a few acres of land compared to the hundreds of acres required for a significant photovoltaic installation. The annual consumption of power in the United States alone is 4000TWh/yr. The land required to generate this large amount of energy is 80,000 km^2 for 10% average efficiency solar cells [2]. Obtaining this amount of land is extremely difficult, especially that which is viable for photovoltaic installations.

Another disadvantage of photovoltaics is the energy produced is non-dispatchable. This means that solar energy must be used immediately upon production. The only method of using solar energy at a later time is with the use of storage devices. Batteries enable photovoltaic energy to be stored and then used as needed rather than immediately. Finally, solar energy is also at a disadvantage in availability of power due to the dependency on the sun as a resource. Since the sun only shines during the daytime, solar energy is unable to produce power at night. This means that other methods of power production must be utilized at night to ensure uninterrupted power.

2.1.5 Applications of Photovoltaics

There exist many applications of photovoltaics in today's world. The most common applications are photovoltaic panels installed in both residential and commercial sites to supply electrical power. However there are multiple everyday items which utilize photovoltaic energy. These items include calculators, watches, and even road signs and lights. The military also frequently utilize the power of photovoltaics in soldier equipment. There are also new small-scale applications of photovoltaics being developed every day.

A major large-scale application of photovoltaics is peak shaving by power companies. Solar energy is most productive during the times when the world consumes the most power. These times mainly include the hot summer months and are referred to as "peak hours." Power companies charge more for electricity during these times and are forced to open additional power plants to produce the required energy. Photovoltaics eliminates this problem by providing the excess power at these critical times without the need of additional coal or gas plants. Other large-scale applications of photovoltiacs include corporate installations. Many companies are beginning to make a conscious effort to become more "green" and environmentally friendly.

2.2 Photovoltaic Tracker Systems

2.2.1 Introduction

One of the most effective applications of photovoltaics are tracking photovoltaic systems. These systems take full advantage of the sun's rays by following the sun's path through the day. Current solar cell technology still struggles to produce highly efficient solar cells. As of today, the most efficient solar cell on the market only has 18% efficiency [2]. This is the biggest limiting factor in solar energy technology and must be overcome for the industry to succeed. While it will take many years to increase the efficiency of solar cells, other measures can be taken to increase the productivity of solar energy systems. Photovoltaic trackers are a highly effective means of increasing the productivity of today's solar energy systems.

2.2.2 Types of Photovoltaic Trackers

Photovoltaic trackers are manufactured in a variety of models to meet specific needs. Tracking systems are available as horizontal-axis trackers, vertical-axis trackers, and even dual-axis trackers which are shown below in Figure 2.2, Figure 2.3, and Figure 2.4 respectively. Horizontal-axis trackers follow the sun from the East to the West. This tracking is used to correct for the change in angle as the sun rises and sets each day. Horizontal-axis trackers are the most common and most investment effective. Fixed-axis photovoltaic systems are only capable of approximately four hours of power production each day, while horizontal-tracking photovoltaic systems are able to produce six hours of power. This additional two hours of production results in up to 30% more system efficiency [2]. In contrast, vertical-axis trackers follow the sun from North to South.

This tracking is used to correct for the angle as the sun shifts from Winter to Summer. Vertical trackers add an additional 6% more productivity over fixed-panel systems [2]. A combination of both horizontal trackers and vertical trackers is available as a dual-axis tracker. These systems follow the sun both East to West as well as North to South. Dual-axis tracking systems are capable of producing approximately 36% more energy over traditional fixed-panel systems [2].

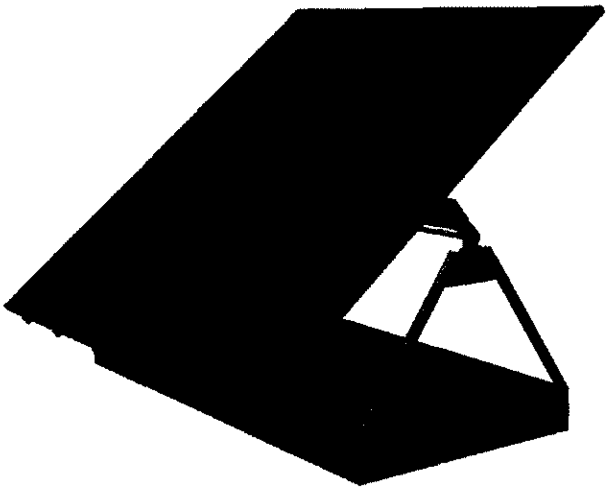


Figure 2.2 Horizontal-Axis Photovoltiac Tracker

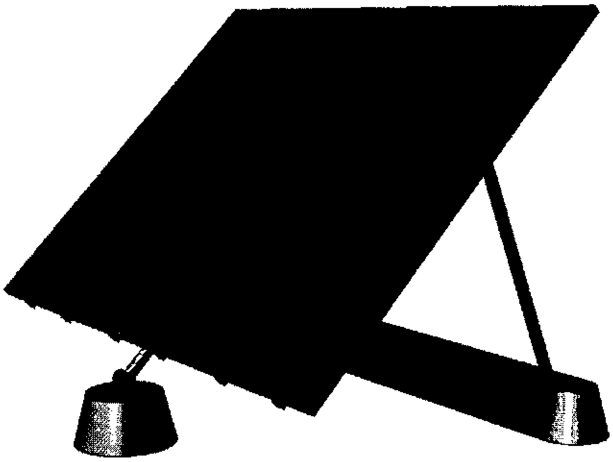


Figure 2.3 Vertical-Axis Photvoltaic Tracker

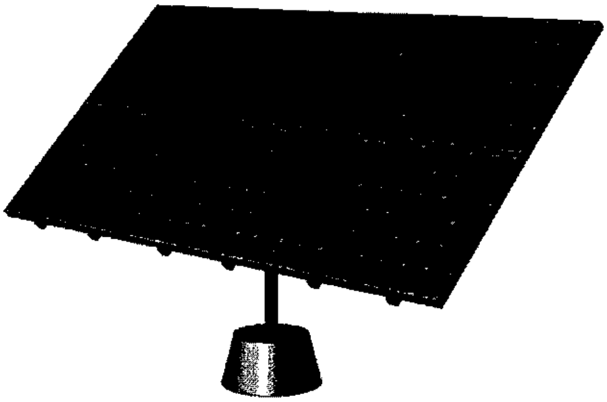


Figure 2.4 Dual-Axis Photovoltaic Tracker

2.2.3 Photovoltaic Tracker Operations

Photovoltaic tracking systems operate according to the path of the sun through the course of the day and year. Since the sun's angle with respect to Earth is constantly altering throughout the day and year, it is impossible to maintain constant power production from a fixed photovoltaic system. Tracking systems enable the solar panels to remain at a perpendicular angle to the sun throughout the day and year. Therefore, maximum power is produced year-round despite drastic changes in the installation location's orientation to the sun. In the Summer months, the sun is higher in the sky and therefore the angle of the panels is not as important. However, in the Winter the sun passes through the sky at a much lower angle. These declination angle differences are illustrated below in Figure 2.5. Tilting the panels to maintain a perpendicular reference to the sun provides a significant increase in power output. The tracking system utilizes actuators and microcontrollers to control this variation in the panel angle.

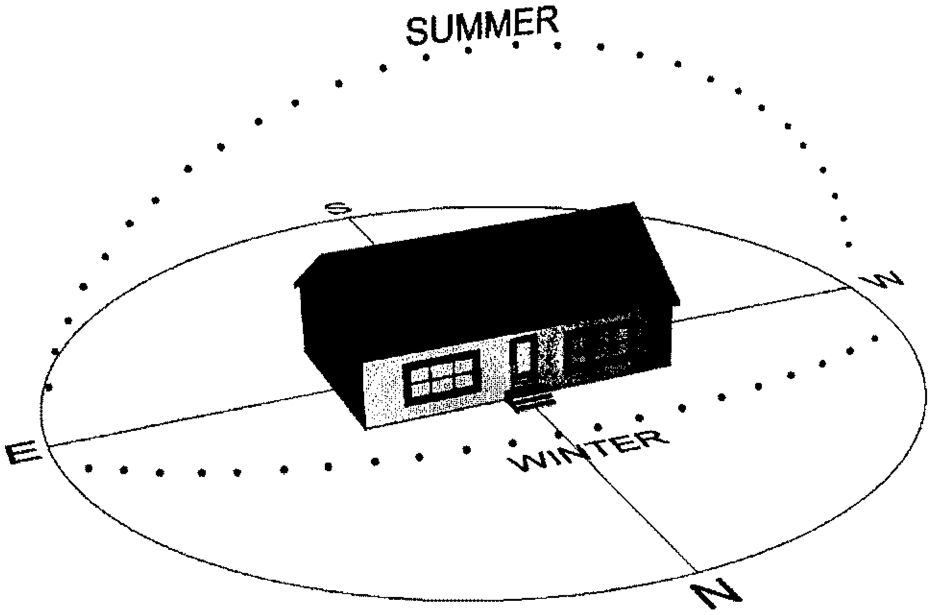


Figure 2.5 Solar Declination Angle by Season

Tracking systems may follow the sun by using sensor tracking or the astronomic ephemeris method. The sensor tracking method relies on an attached irradiance sensor to detect the location of the sunlight and orient the panels accordingly. In contrast, the astronomic ephemeris method uses the latitude and longitude of the panels' location to calculate their relationship to the sun for that precise date and time. All of these angle calculations are performed by the microcontroller which then transfers them into the appropriate actuator stroke length. The microcontroller then signals the actuator to initialize in or out to achieve the desired panel orientation angle. A diagram of a photovoltaic tracker in operation is given below in Figure 2.6.

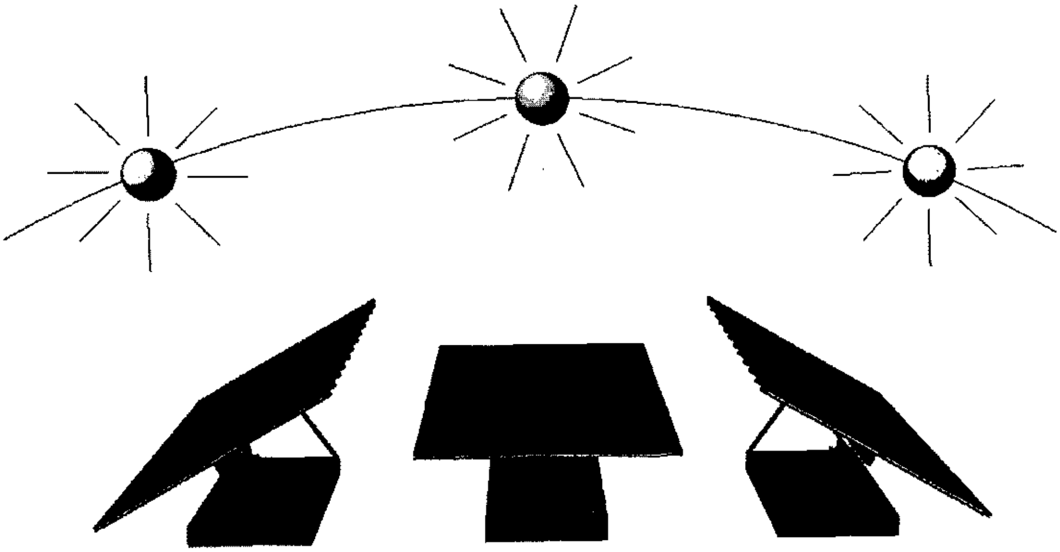


Figure 2.6 Schematic of Phovoltaic Tracker Operations

2.2.4 Advantages of Photovoltaic Trackers

While fixed photovoltaic systems are very effective, they are not capable of providing the power produced by a tracking photovoltaic system. Photovoltaic systems only harness majority of their power during the peak production hours of 11:00AM to 3:00 PM [2]. However, fixed photovoltaic systems are only capable of power production for approximately four hours due to the angle offset to the sun. This results in a significant loss in energy throughout each day. The main advantage of tracking photovoltaic systems is their ability to harness approximately six hours of power each day.

Photovoltaic trackers allow for increased productivity equivalent to larger fixed-panel systems without the increased cost and required space. Trackers also allow for more leeway with installation locations. Since the solar panels follow the sun, the systems may be installed on both flat and mildly sloped surfaces. The tracking feature is able to correct for minor angles in ground surface. This significantly reduces the cost of installation since grading of the land is not necessary.

2.2.5 Disadvantages of Photovoltaic Trackers

While photovoltaic trackers are more efficient, they also are accompanied by a higher investment cost. This increase in price is typically 30% more than fixed-panel systems [2]. However, this additional cost is usually offset by the 30% increase in power production enabling the owner to recoup their investment in the same timeframe as those with a fixed-panel system [2]. Another disadvantage of photovoltaic tracking systems is the increased cost of maintenance. The advanced components which enable the tracking features require routine upkeep and monitoring to ensure accuracy. This increase in installation and operation costs means proper monitoring of the system is necessary to ensure the highest power yield.

2.2.6 Applications of Photovoltaic Trackers

Tracking photovoltaic systems have numerous applications in today's world. These systems may be utilized in many of the same applications as fixed-panel photovoltaic devices. Such applications include large-scale solar panel installations as well as small-scale task-oriented installations. Photovoltaic trackers are particularly useful for infrastructure applications which include emergency phones, road signs and lights, and even lighthouses. Tracking systems are capable of providing the power required for these tasks without consuming a large amount of space. Photovoltaic trackers are also a good alternative for fixed-panel systems in large commercial applications. The increased efficiency of tracking systems provides significantly more electricity for usage. This makes photovoltaic tracking systems an economical alternative to fixed-panel systems.

2.3 Components of Photovoltaic Tracker Systems

2.3.1 Programmable Logic Controller

One of the most important components of a photovoltaic tracker is the programmable logic controller (PLC). Without this device, the system would be unable to determine the appropriate tilt angle throughout the day. The PLC is also used to convey the angle adjustment commands to the tracker. There are numerous types of PLC's available in today's market by different manufacturers. Each of these PLC's offer a robust and reliable means of controlling electric devices. PLC components are capable of operating in harsh environments for extremely long durations of time. This makes PLC's the ideal means of controlling photovoltaic tracker systems.

There are many types of PLC's available on the market today. The two major manufacturers are Siemens and Allan Bradley. While both are very reliable devices, this thesis incorporates Siemens components due to the ease of integration. The PLC used to control the photovoltaic tracker actuators is specifically the Siemens S7-1200. This PLC is capable of controlling multiple inputs and outputs and is especially useful in automation applications. The S7-1200 operates with the use of several communication modules and can be expanded to suit the application. The communication modules used in this work include an RS232 interface, an RS485 interface, and an Ethernet interface. All of these modules facilitate the necessary communication between the components of the system. These components include the field-based PLC's, master PLC, actuators, and HMI's (human machine interface). The HMI is used to display real-time data related to the PLC and associated operations.

2.3.2 Actuator

Another important component of a photovoltaic tracker system is the actuator. Without this device, the solar tracker would be unable to adjust to the proper tilt angle. Linear actuators are available in several varieties. Such variations include pneumatic actuators, hydraulic actuators, mechanical actuators, and electro-mechanical actuators. Photovoltaic tracker applications typically utilize electro-mechanical actuators. Such actuators are highly robust, reliable, and can support extreme weights. The solar arrays of each photovoltaic tracker are attached to a single actuator. However, dual-axis trackers typically consist of two actuators to control movement in both the horizontal and vertical directions. Each actuator has a DC power cable and an RS232 communication cable. The actuators of each tracker are attached in a daisy-chain to eliminate the number of wires on the field. The actuators then communicate with the PLC via Modbus or PROFIBUS serial protocol through the RS232 cables. The PLC sends the signal to each actuator with the necessary stroke length to maintain proper solar panel orientation.

2.3.3 Communication

Photovoltaic trackers rely on actuators to follow the sun throughout the day. This movement is not possible without communication between the PLC and the actuator. Such communication is performed according to a master-slave chain of commands. This communication can follow either Modbus or PROFIBUS protocol. In a field of photovoltaic trackers, one actuator is associated with each tracker. The actuators are then connected in daisy-chain to allow for long-term communication in the field. As the PLC determines the proper tilt angle, a signal is sent to each actuator to adjust to the new declination angle.

2.3.4 GPS

In order to obtain the proper tilt angle a global positioning system (GPS) is necessary. Trackers which utilize an algorithm as a means of calculating the precise tilt angle require the system GPS location. This GPS data is used to determine the latitude and longitude of the photovoltaic system. The location of the system is then used with the appropriate time of sunrise and sunset to determine when and how the tracker should tilt. A GPS is assigned to each PLC since the trackers are too close together to distinguish from one another. Therefore, up to sixteen trackers may be assigned to one GPS in the field. The use of the GPS also enables the user to locate a specific row of trackers or PLC within a large solar field.

2.3.5 Combiner Box

Photovoltaic tracker systems are comprised of numerous solar panels and thus include multiple output strings. These strings are created when the individual solar panels are connected in series. As previously stated, the number of strings per tracker is determined by the size of the inverters in use. However, these individual strings must be combined into one large string before attachment to the grid. This task is accomplished with the use of a combiner box. The strings are attached to the inputs of the combiner box. A copper or aluminum bus bar is then used to combine the strings into a single string. The combined string is then able to be converted from DC to AC power with the use of the inverter. Combiner boxes may be integrated into a photovoltaic tracker system a variety of ways. The box may be a stand-alone system or integrated with other components such as the fuse panel or inverter.

CHAPTER 3

PHOTOVOLTAIC TRACKER SYSTEM MONITORING

3.1 Motivation

While photovoltaic tracker systems are very effective methods of obtaining solar energy, they are not immune to faults. These faults are capable of significantly reducing the productivity of the system. To date, photovoltaic tracker systems have no means of monitoring current faults on a string-based level. This is a highly necessary tool to ensure the greatest level of solar efficiency. In a field of thousands of photovoltaic trackers, there is currently no way of knowing when a single string fails. Today's systems simply monitor the power of a photovoltaic tracker system as a whole. While a single string may not immediately effect the overall productivity of a system, the long term repercussions can be very costly.

Consider an installation of 2,000 photovoltaic trackers within a ten acre field. Each tracker consists of an array of 36 individual solar panels. Each panel is rated for 250W of power production and the owner chose to use 20kW inverters. Therefore, the panels of each tracker will be combined into two individual strings. This means that for the 2,000 trackers, there will be 4,000 strings to monitor containing 72,000 solar panels. At this scale, the need for a monitoring system is very apparent. Since monitoring each of the solar panels is not cost effective, monitoring each of the strings is the most appropriate method. A schematic of current photovoltaic tracker systems is given in Figure 3.1. From this diagram we can see how complex tracking systems are and the variety of areas where problems may arise. A majority of today's photovoltaic tracker systems rely on the inverters as a means of monitoring. However, this method can be unreliable as inverters account for approximately 50% of problems in photovoltaic systems. Therefore, a precise method of monitoring each photovoltaic string is necessary to ensure the system is performing without faults.

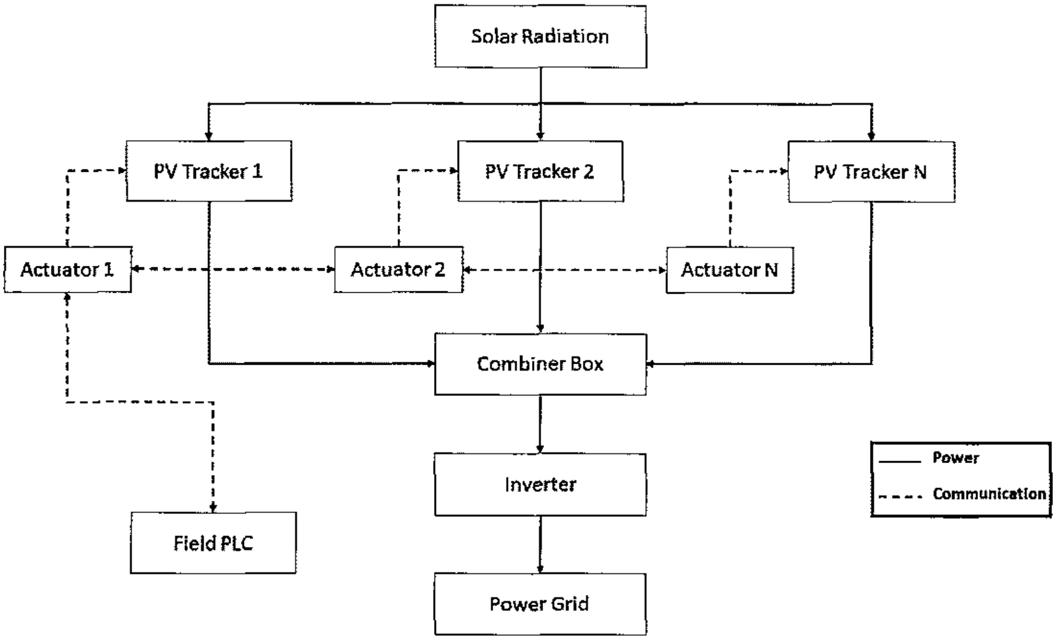


Figure 3.1 Schematic of Photovoltaic Tracking System

3.2 Problem Statement

The goal of this thesis is to develop an effective method of monitoring faults within a tracking photovoltaic system. The need for such a system has arisen with the recent increase of photovoltaic tracker installations. While determining errors and faults within a small fixed-system of solar panels is relatively easy, the same task with a large tracking-system is highly complex. Many variables become important when dealing with a field of several thousand photovoltaic trackers. Proper monitoring and analysis of these variables ensures the highest efficiency and overall system yield.

To date solar cells are still relatively inefficient. However, photovoltaic trackers are an effective means of increasing the efficiency of a solar energy system. Trackers are able to produce the same amount of power as larger fixed-panel systems without the added consumption of land. The increased yield of photovoltaic trackers comes at a high price that is well worth the investment if properly maintained.

3.3 Overview of Monitoring System

The purpose of this thesis was to resolve the lack of photovoltaic tracker fault detection systems. This was accomplished by developing a monitoring system that works with the existing hardware of today's photovoltaic tracker systems. This monitoring system is based upon previous research performed by Hareen Illa at Old Dominion University [1]. Mr. Illa worked to accomplish a similar goal without the combiner feature and system integration. The system developed in this research is an improvement upon the previous system and is therefore comprised of several key components which include:

1. 24V Power Supply
2. 24V-15V Voltage Regulator Unit
3. Closed-Loop Current Sensor Unit
4. Multiplexer Unit
5. Isolated Voltage Measurement Unit
6. Programmable Logic Controller

A schematic of the monitoring system is given below in Figure 3.2. From this diagram we see that the fault detection system developed in this thesis has been integrated with the existing fuse panel. The system is capable of monitoring up to 16 individual photovoltaic strings and is rated to withstand a maximum of 20A per string and 1000V. Figure 3.3 shows the flow of power and communication throughout the monitoring system. All of the components utilize the existing 24V DC power supply used by the actuator. This usage of existing components significantly reduces the cost of the system and optimizes the application of each component.

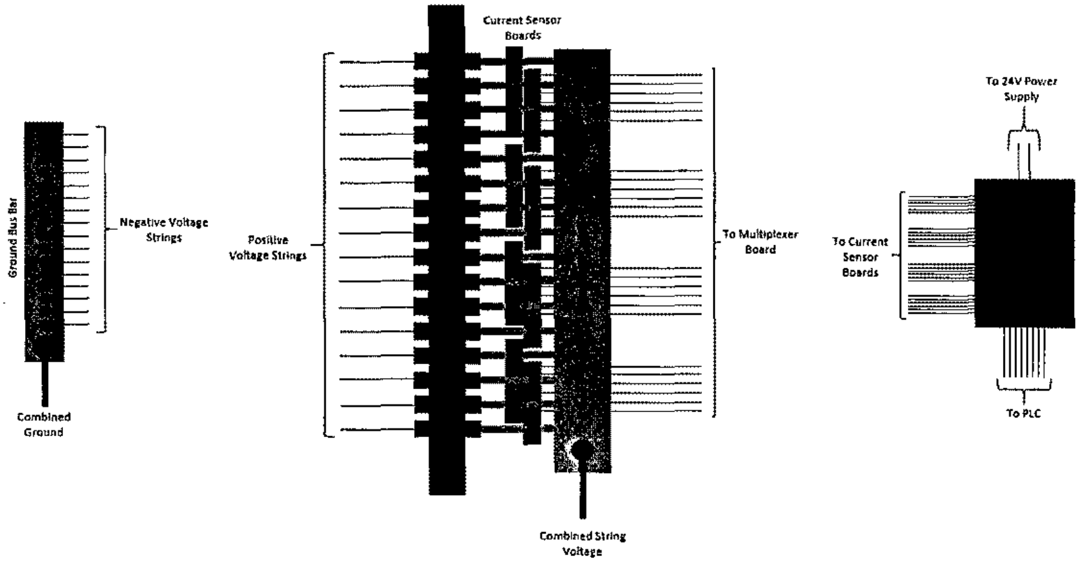


Figure 3.2 Schematic of Photovoltaic Tracker Monitoring System

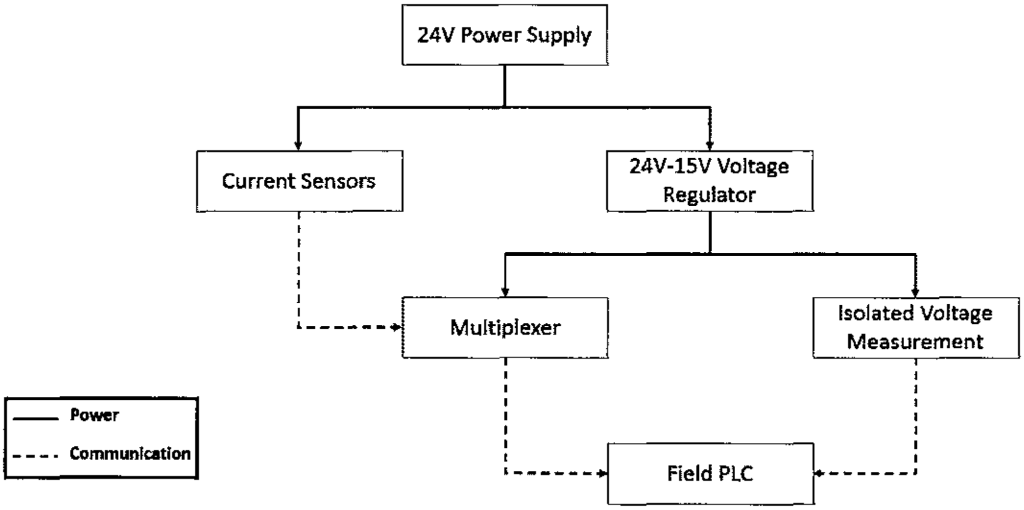


Figure 3.3 Block Diagram of Photovoltaic Tracker Monitoring System

CHAPTER 4

CURRENT SENSORS

4.1 Introduction

The first step of this thesis was to select a method of measuring the current produced by the photovoltaic tracking systems. An effective and reliable stream of current data is required to effectively monitor for faults. This is accomplished with the use of current sensors which measure the current of each photovoltaic string. There are many devices which are applicable to this task. Such devices are discussed below along with pertinent technical data.

4.2 Hall-Effect

Many current sensors operate according to the Hall-Effect. This technique is a highly accurate means of determining the current value within a given wire. The Hall-Effect is extremely well known and can be used to measure both DC and AC current. The Hall-Effect incorporates the relationship between electric current and magnetic fields. As an electrical conductor conducts current, a magnetic field is produced perpendicular to the flow of current. The conductor then produces a voltage difference transverse to the flow of current. This voltage difference is known as the Hall Voltage and is given by the equation:

$$V_H = -\frac{IB}{ned} \tag{1}$$

Here I is the electric current, B is the magnetic field, n is the charge density, e is the charge of an electron, and d is the thickness of the electrical conductor. This voltage is directly proportional to the current within the conductor. Therefore, the Hall Voltage can be used to determine the current within the electrical conductor. The Hall Effect can be used to measure both AC and DC current which is highly desirable in photovoltaic applications.

4.3 IC Current Sensors

An effective form of obtaining the string currents is the use of integrated circuit (IC) current sensors. These sensors are open-loop meaning they "break" the circuit in order to measure the associated current. IC sensors are typically smaller and less expensive than closed-loop current transducers. Integrated circuit sensors use the Hall Effect to sense the voltage proportionate to the AC or DC current. The sensors are available in a variety of packaging both through-hole and surface mount. This makes IC sensors easily adaptable to many current measurement applications. However, IC sensors are a type of open-loop sensor which requires the circuit to be broken. The sensor interrupts the flow of current throughout the circuit in order to determine the proportionate voltage.

4.4 Closed-Loop Current Sensors

Another method of obtaining the string current data is with the use of closed-loop current transducers. These sensors also use the Hall-Effect to determine the Hall Voltage of the photovoltaic strings. The sensors incorporate copper wound core which surrounds the current conductor being measured. The conducting wire is simply placed through the hole within the sensor. Closed-loop sensors are typically larger and more expensive than IC current sensors. However, the closed-loop design allows for accurate current measurement without breaking the circuit.

4.5 Current Sensor Testing

The selection of the proper sensors was difficult due to the vast amount of options on the market. This decision was made easier by testing a variety of sensors and comparing the resulting data. Each sensor was subjected to both short-duration and long-duration tests to determine feasibility for the application. Five sensors were selected for testing, both IC current sensors and closed-loop current sensors. The IC current sensors include the Allegro ACS712T, the Allegro ACS758xCB, and the LEM HLSR 10-P. The closed-loop current sensors tested include the F.W. Bell CLSM-50, the Honeywell CSNP661, and the LEM LA 25-P. Each sensor was tested from 0A to 20A for one minute intervals in the short duration tests. The sensors were then tested at 10A for six hours during the long duration tests. The closed-loop sensors were then further tested to determine the effect of wire placement within the sensor opening on the current measurements.

The testing was performed by simulating photovoltaic string currents with the use of a high current source. The other components used in the testing procedure included a DC voltmeter as well as a resistive load. The load was created with the use of five 1Ω power resistors connected in series and attached to a heat sink. This applied a load without a high resistivity to drastically drop the current sensor readings. Kelvin leads were also used to eliminate any resistance that would result from the wiring used.

The first IC current sensor tested was the Allegro ACS712T. This sensor is a surface mount device capable of measuring currents up to ±20A. The sensor has a sensitivity rating of 100mV/A and requires a supply voltage of +5V. The Allegro ACS712T test data is given below in Figure 4.1 and Figure 4.2. From the short duration test data we see that the sensor is highly linear from 0A to 20A. The sensor is also very accurate as well as precise. This is evident from the long duration test data since there is only minor variation in the sensor measurement outputs.

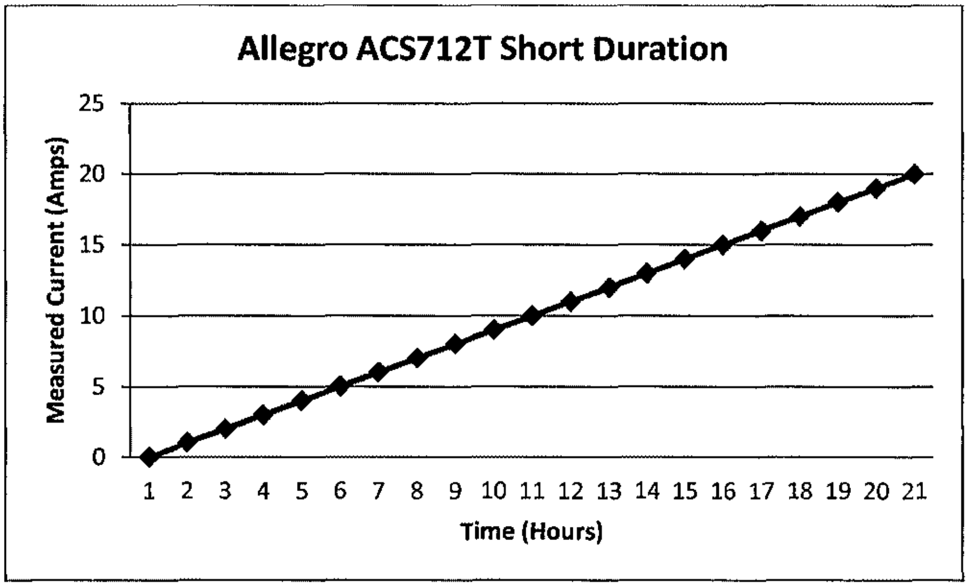


Figure 4.1 Allegro ACS712T Short Duration Test Data

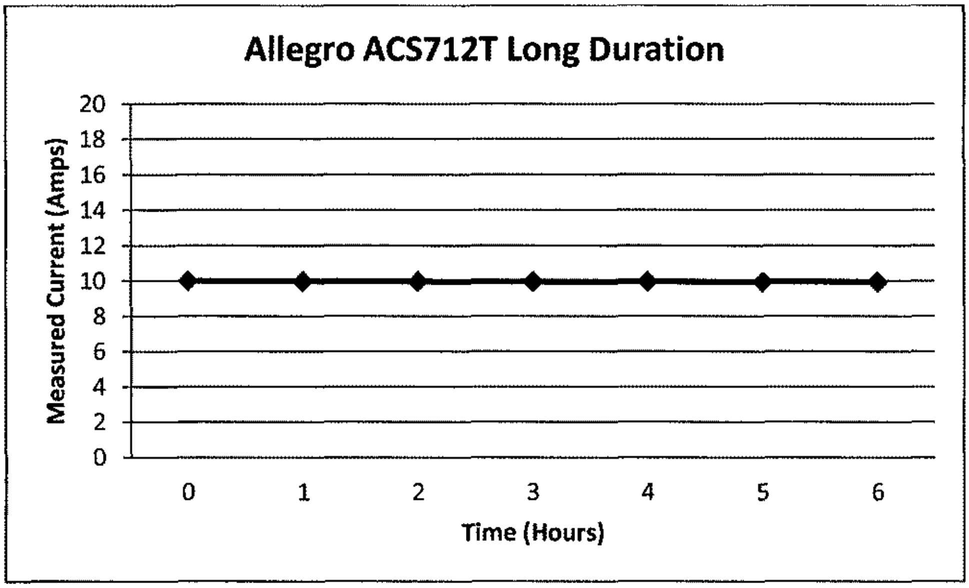


Figure 4.2 Allegro ACS712T Long Duration Test Data

The second IC current sensor test was the Allegro ACS758xCB. This sensor is a through-hole device capable of measuring currents up to 50A. The sensor has a sensitivity of 50mV/A and requires a supply voltage of +5V. The Allegro ACS758xCB test data is given below in Figure 4.3 and Figure 4.4. From this data we see that the sensor outputs are both linear and precise. There is little variation in the measured currents from the long duration test.

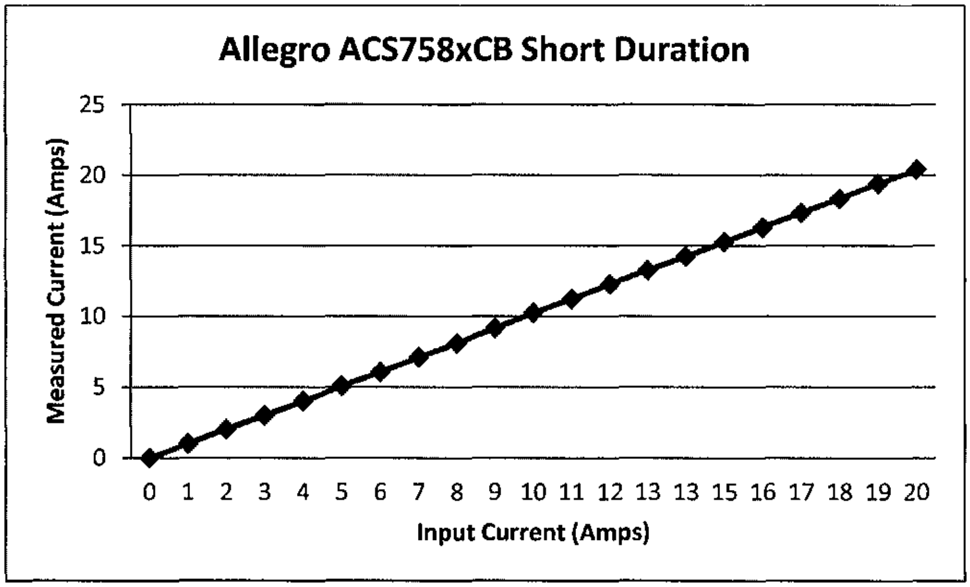


Figure 4.3 Allegro ACS758xCB Short Duration Test Data

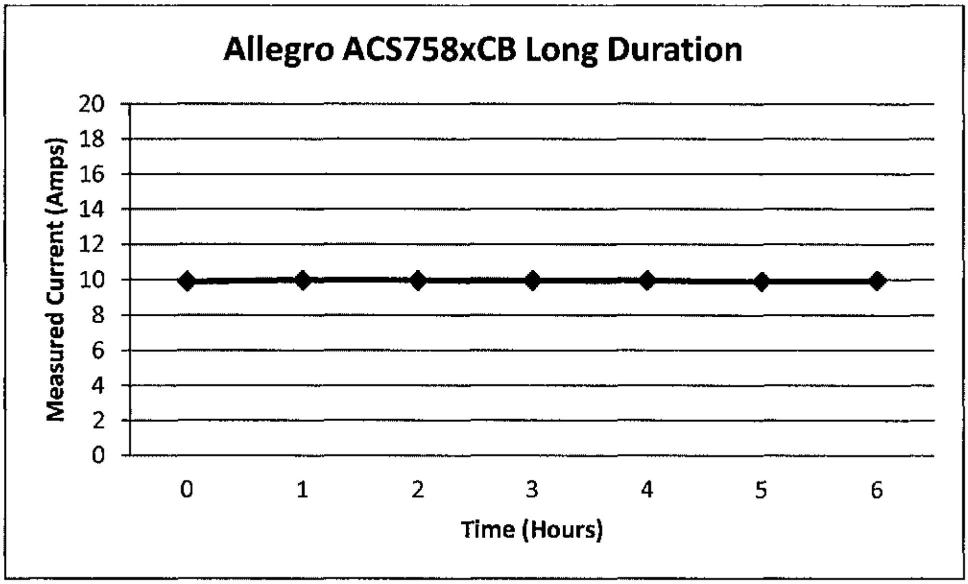


Figure 4.4 Allegro ACS758xCB Long Duration Test Data

The third IC current sensor tested was the LEM HLSR 10-P. This sensor is a through-hole device capable of measuring up to 25A. The sensor has an accuracy of 1% and requires a supply voltage of 5V. The LEM HLSR 10-P test data is given below in

Figure 4.5 and Figure 4.6. From the short duration data we see that the sensor is linear and slightly inaccurate. However, the long duration data shows that the sensor is highly precise with consistent measurements over extended usage periods.

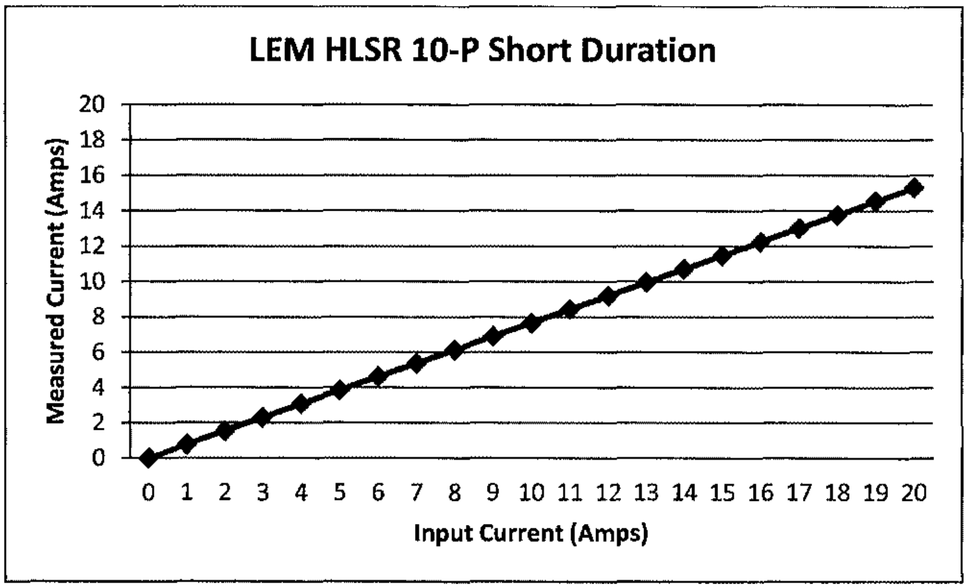


Figure 4.5 LEM HLSR 10-P Short Duration Test Data

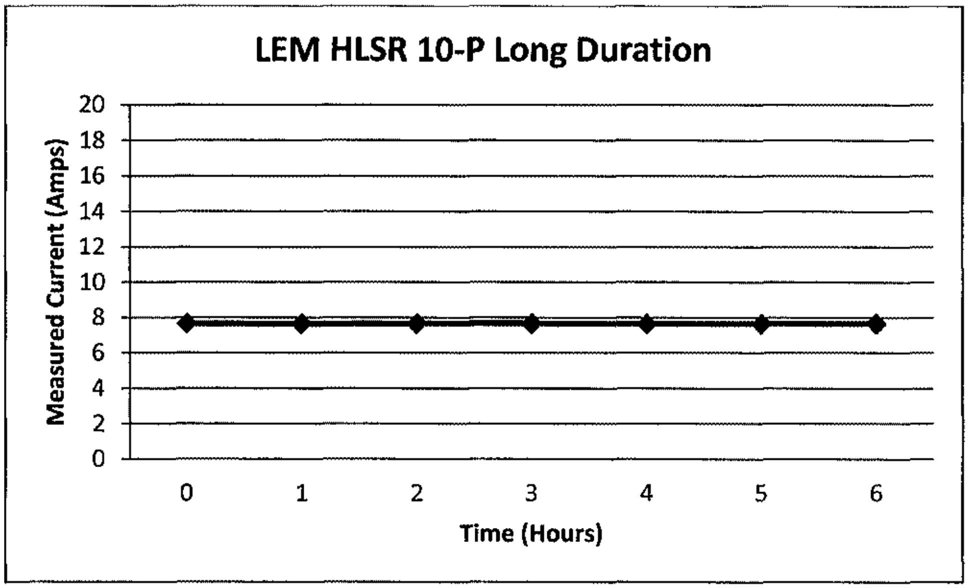


Figure 4.6 LEM HLSR 10-P Long Duration Test Data

The first closed-loop current sensor we wanted to test was the F.W. Bell CLSM-50. This sensor is a through-hole device capable of measuring up to ±50A. The sensor has an accuracy of ±0.5% and requires a supply voltage of ±12V to ±15V. Further testing was not performed on this sensor as the power supply requirements are not adaptable to the monitoring system design. The F.W. Bell CLSM-50 must be run in bipolar mode while the other sensors are capable of operating in unipolar mode. This means that the sensor requires the supply voltage of ±12V to ±15V which is very expensive to provide. Therefore, this sensor was eliminated from consideration prior to testing.

The second closed-loop current sensor tested was the Honeywell CSNP661. This sensor is a through-hole device capable of measuring up to ±90A. The sensor has an accuracy of ±0.5% and requires a supply voltage of ±12V to ±15V. The Honeywell CSNP661 short duration testing data is given below in Figure 4.7, Figure 4.8, and Figure 4.9. From these graphs we see that the sensor is highly linear although slightly more inaccurate than the IC current sensors. Using the comparison in Figure 4.10 we can see that the placement of the wire within the current sensor has no effect on the sensor outputs. The long duration test data is given below in Figure 4.11 and verifies that the sensor is highly precise in measurements.

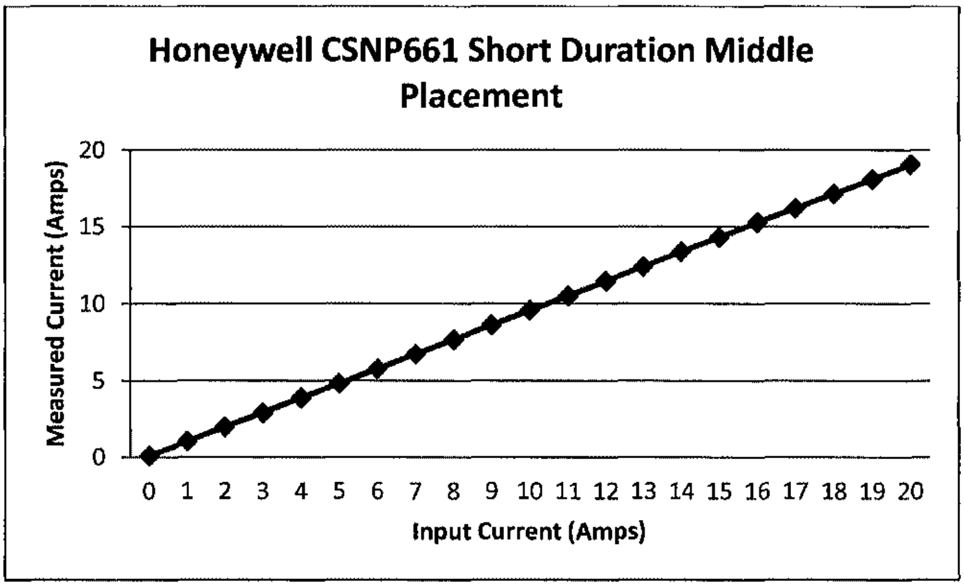


Figure 4.7 Honeywell CSNP661 Short Duration Middle Placement Test Data

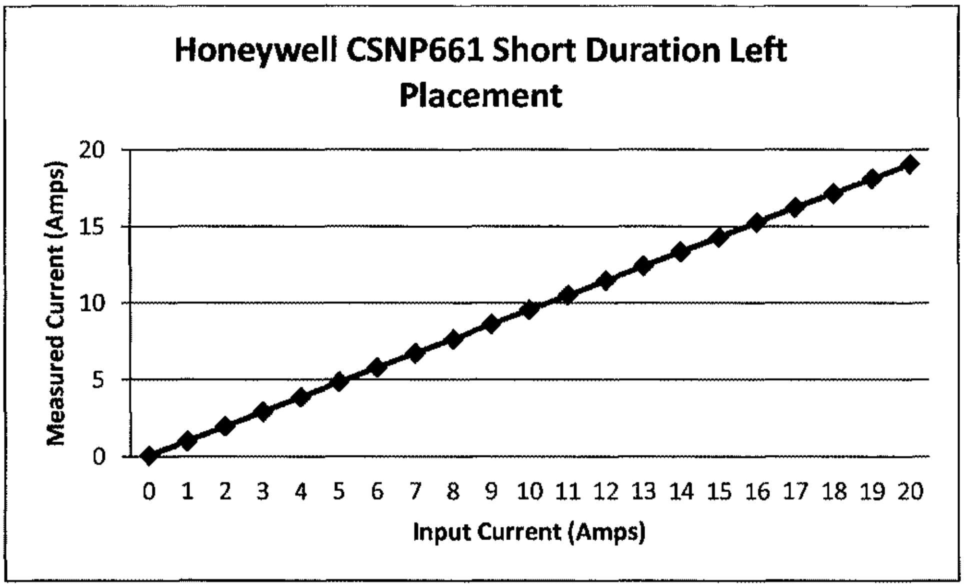


Figure 4.8 Honeywell CSNP661 Short Duration Left Placement Test Data

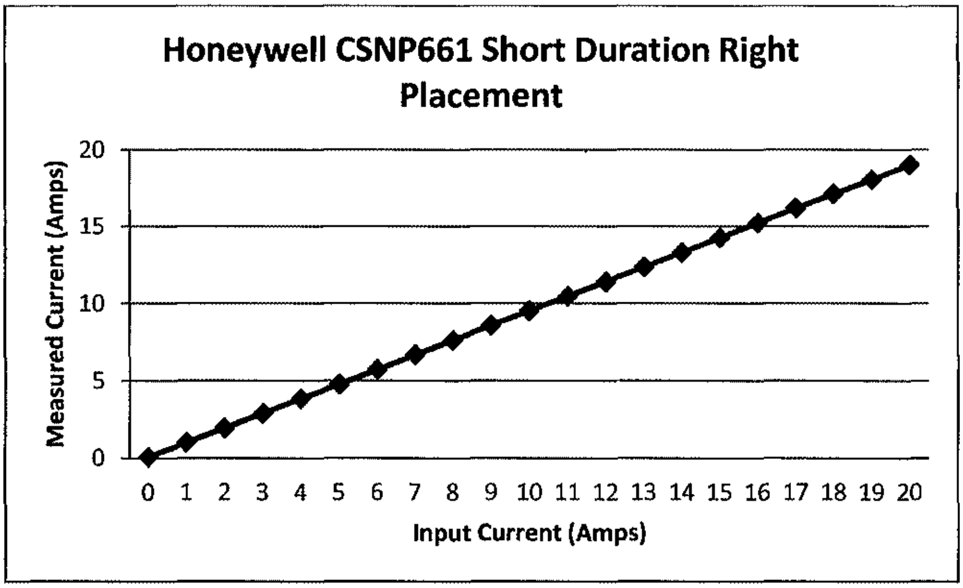


Figure 4.9 Honeywell CSNP661 Short Duration Right Placement Test Data

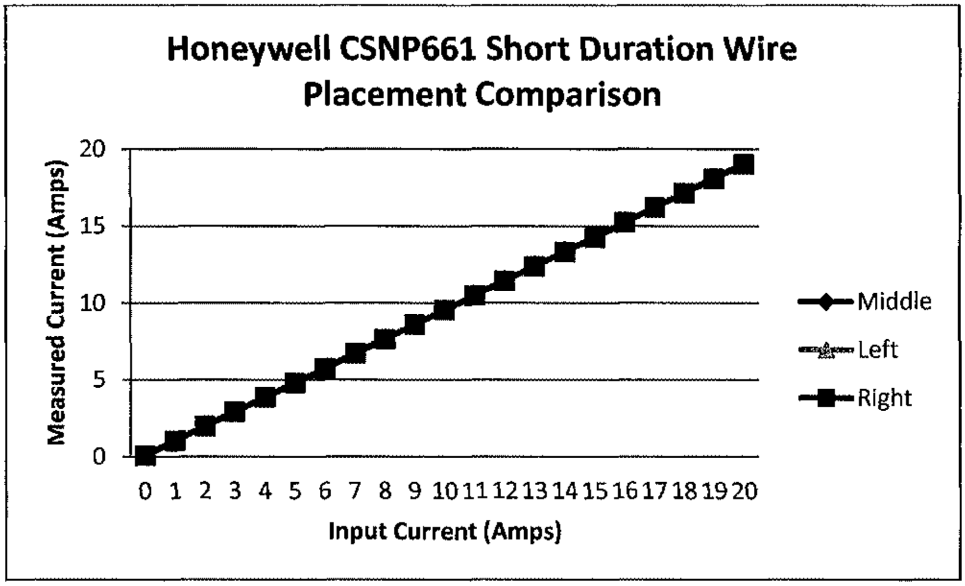
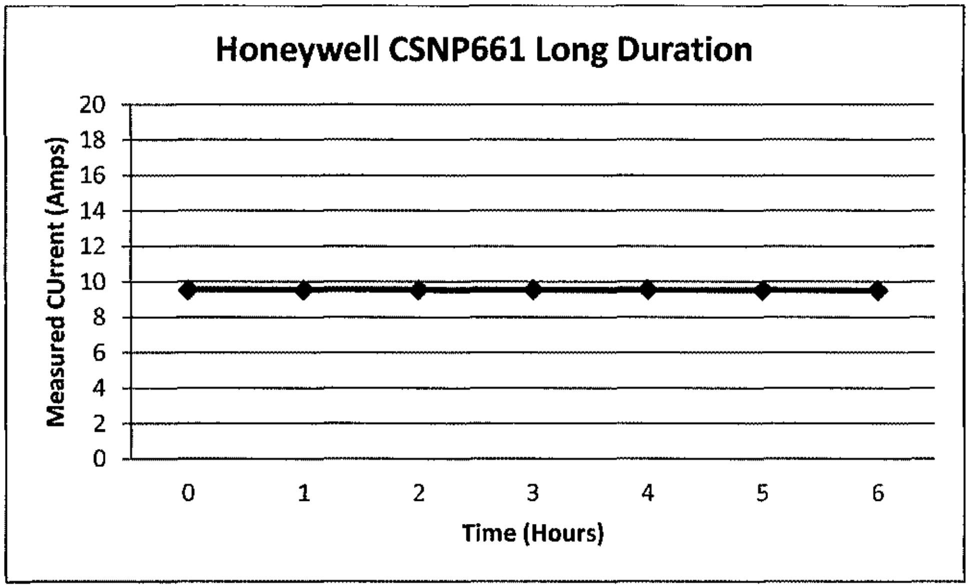


Figure 4.10 Honeywell CSNP661 Short Duration Wire Placement Comparison Test Data



Graph 4.11 Honeywell CSNP661 Long Duration Test Data

The third closed-loop current sensor tested was the LEM LA 25-P. This sensor is a through-hole device capable of measuring up to ±25A. The sensor has an accuracy of ±0.95% and requires a supply voltage of ±12V to ±15V. The LEM LA 25-P short duration test data is given below in Figure 4.12, Figure 4.13, and Figure 4.14. From these graphs we see that the sensor is highly linear although slightly inaccurate. The wire placement comparison can be seen in Figure 4.15. This data indicates that the placement of the conducting wire within the sensor has no effect on the output measurements. The long duration test data given in Figure 4.16 shows that the LEM LA 25-P is very precise over extended periods of use.

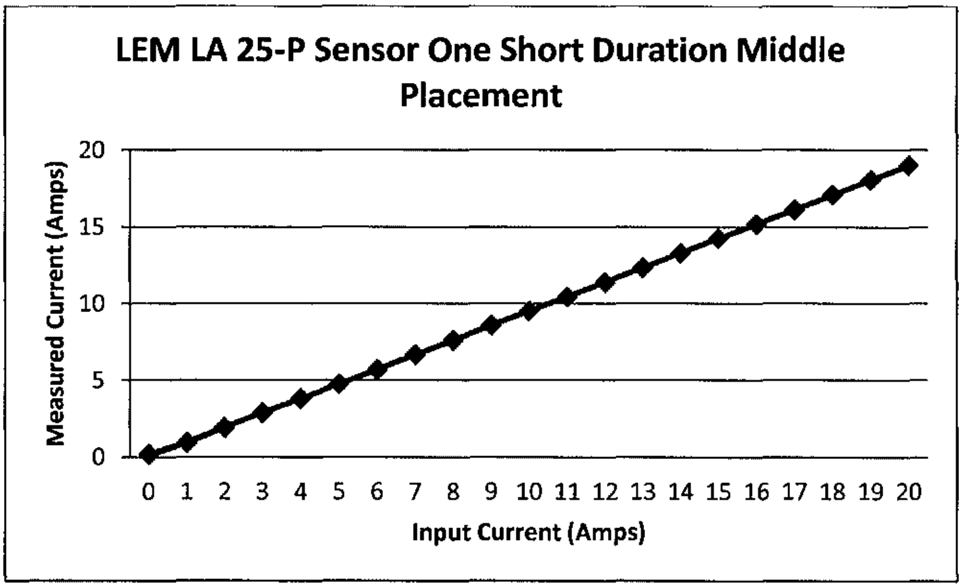


Figure 4.12 LEM LA 25-P Sensor One Short Duration Middle Placement Test Data

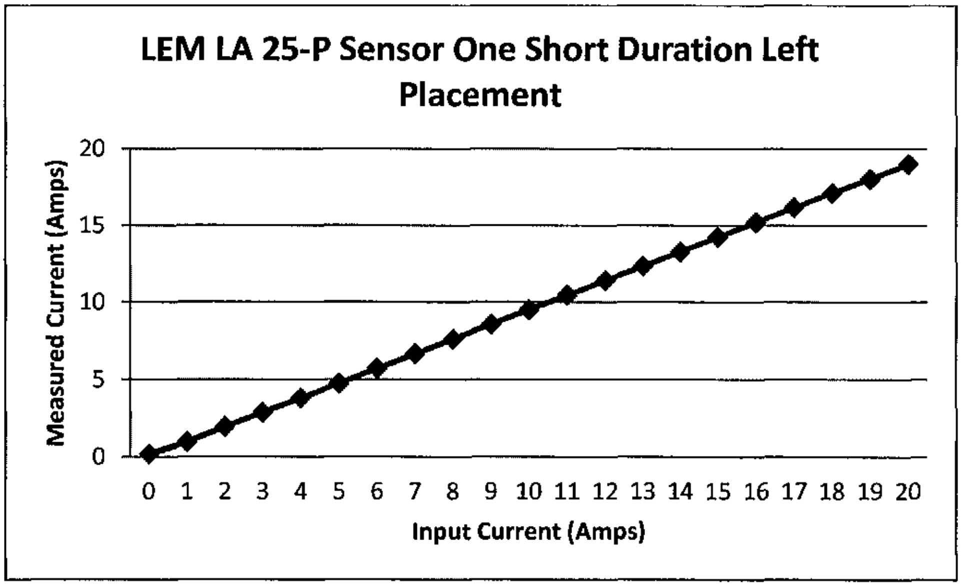


Figure 4.13 LEM LA 25-P Sensor One Short Duration Left Placement Test Data

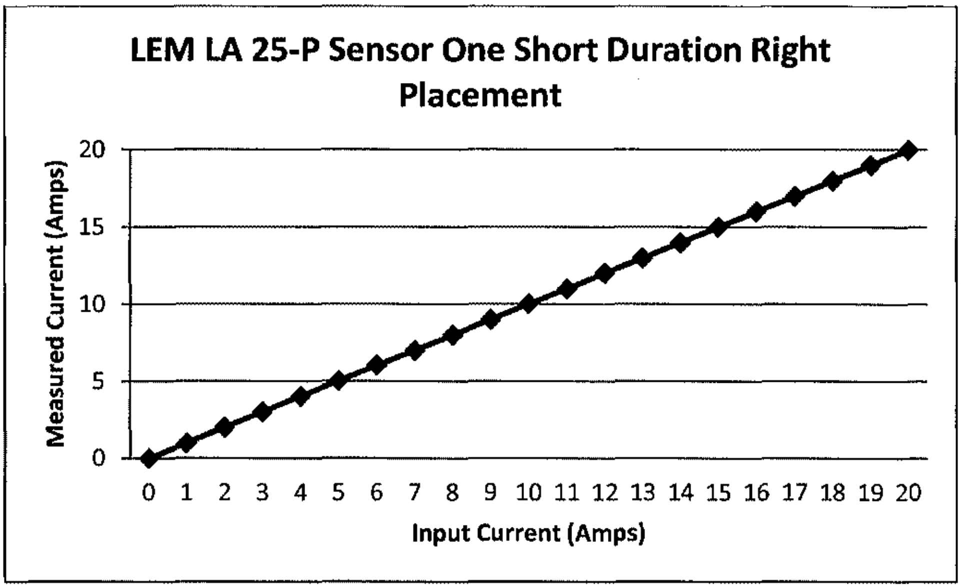


Figure 4.14 LEM LA 25-P Sensor One Short Duration Right Placement Test Data

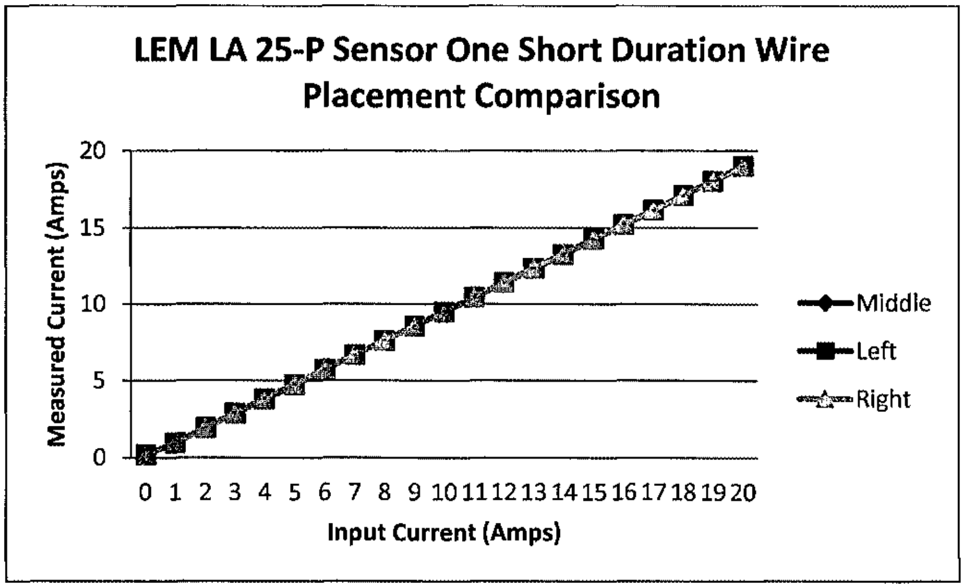


Figure 4.15 LEM LA 25-P Sensor One Short Duration Wire Placement Comparison Test Data

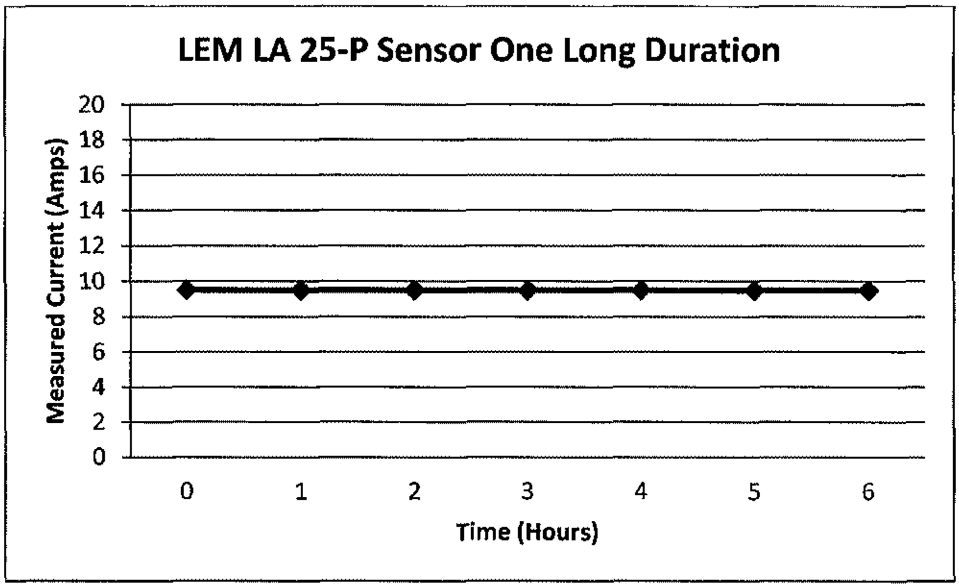


Figure 4.16 LEM LA 25-P Sensor One Long Duration Test Data

4.6 Selection of Current Sensors

Although IC current sensors are very accurate and reliable, these sensors have several weaknesses. The major weakness of the IC sensors is the interruption of the circuit in order to retrieve the current measurements. This is not appropriate for photovoltaic tracker applications since failure of the sensor would result in disconnection of the photovoltaic string. The purpose of the monitoring system is to provide accurate current and voltage measurements without disturbing the functions of the photovoltaic tracking system. Therefore, the three IC current sensors were eliminated from consideration for selection. The remaining sensors for consideration included the Honeywell CSNP661 and the LEM LA 25-P. Both sensors performed almost identically during testing and have similar specifications. However, the Honeywell sensor is not widely available and is slightly more expensive than the LEM sensor. Thus the decision was made to utilize the LEM LA 25-P current transducer in the photovoltaic tracker monitoring system application.

Once the selection of the LEM LA 25-P was made, further testing was performed on this sensor. The purpose of the additional testing was to determine additional useful information to aid in the design of the monitoring system. Two additional LEM LA 25-P sensors were tested for the short duration middle placement scenario. These tests were performed to confirm that the sensors are linear, precise, and accurate. The testing data for sensors two and three are given below in Figure 4.17 and Figure 4.18. This data was then compared with the data from sensor one to observe the agreement amongst multiple sensors. The three sensor comparison data can be seen in Figure 4.19. This graph indicates that the LEM LA 25-P sensors' outputs are in agreement. Although the LEM sensor is slightly inaccurate, this can be easily corrected since the outputs are linear.

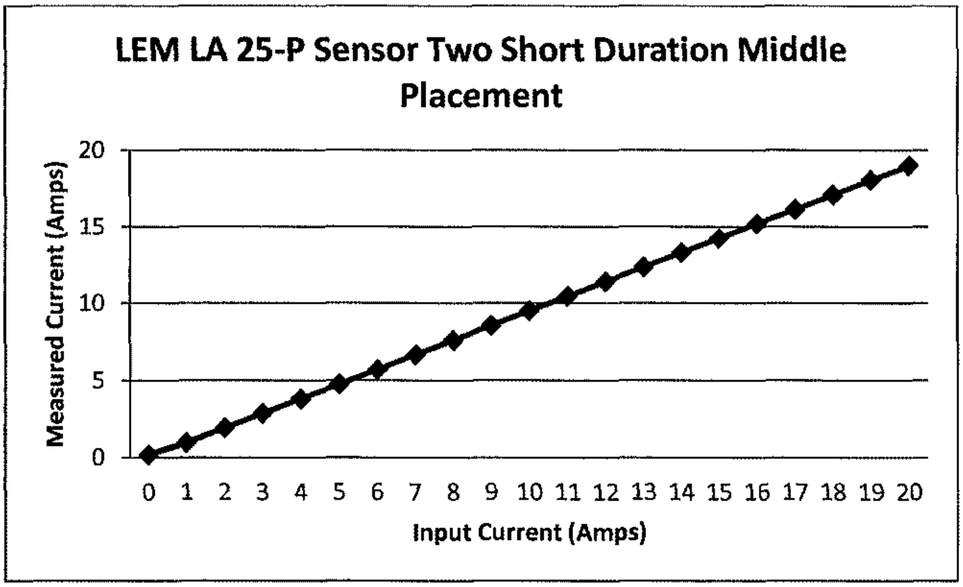


Figure 4.17 LEM LA 25-P Sensor Two Short Duration Middle Placement Test Data

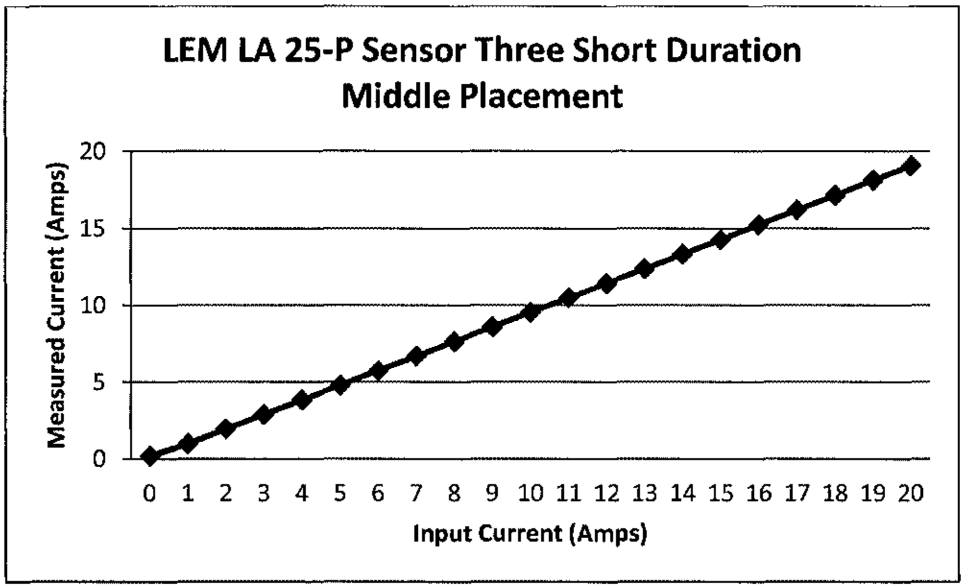


Figure 4.18 LEM LA 25-P Sensor Three Short Duration Middle Placement Test Data

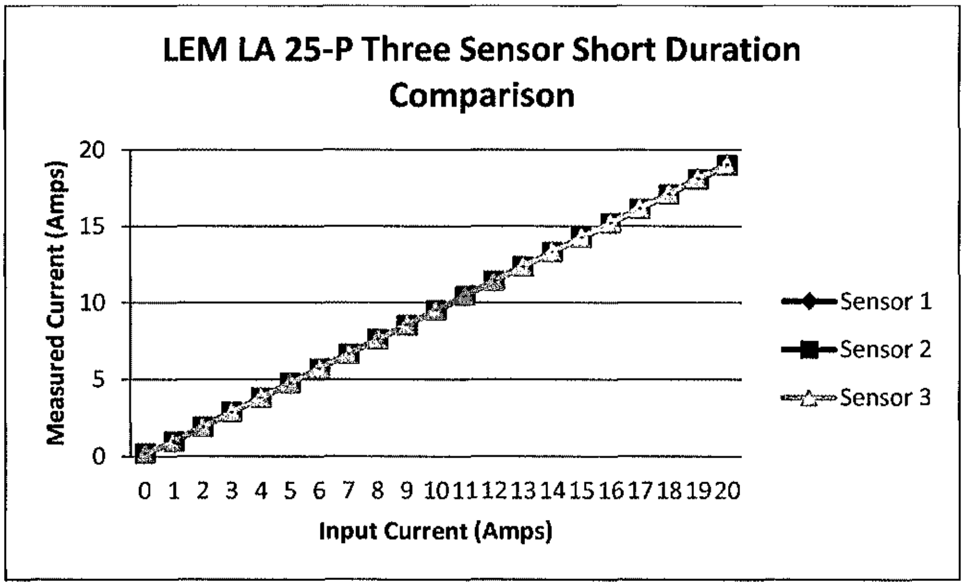


Figure 4.19 LEM LA 25-P Three Sensor Short Duration Comparison Test Data

CHAPTER 5

DESIGN AND FABRICATION OF MONITORING SYSTEM

5.1 Schematic Design

5.1.1 Current Sensor Boards

The fault detection system is divided into two separate PCB boards with the first being the current sensor board. All schematic design work was completed using the freeware *ExpressSCH*. The sensors were designed on a separate board from the other components to enable proper integration with the existing fuse panel. Since the PLC is limited in the number of digital inputs, the number of monitored strings is limited to sixteen. Therefore, the sensor board must incorporate sixteen LEM LA 25-P current sensors. However, many photovoltaic tracker applications will not always have exactly sixteen strings in one row. To enable the monitoring system to effectively be applied to a variety of photovoltaic tracking installations, the boards were broken down to include only four sensors per board. This reduces cost and space when less than sixteen sensors are needed.

The pin out of the LEM LA 25-P current sensor is given below in Figure 5.1. The sensor contains three pins which include positive voltage input, negative voltage input, and sensor output. The LEM sensor was designed to be used in a bipolar mode requiring ±12V to ±15V power supply. However, in this application the sensor is used in a unipolar mode requiring +24V to +30V power supply. This allows further utilization of the already existing +24V DC power supply used to power the actuator. The +24V is then connected to the positive input voltage pin and ground is connected to the negative input voltage pin of the current sensor.

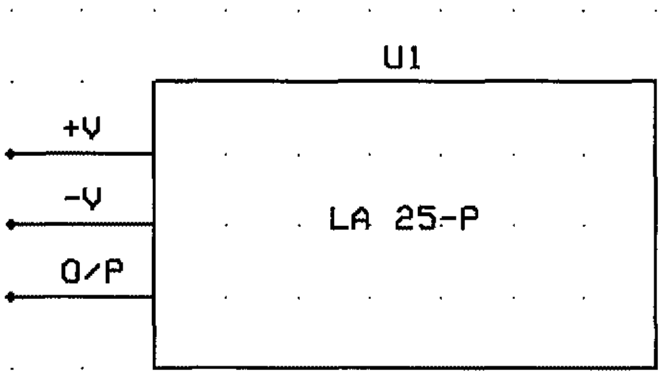


Figure 5.1 LEM LA 25-P Current Transducer Pin Out

The current sensor board schematic is given below in Figure 5.2. The layout of the four sensors can be seen in this schematic as well as the connection to the multiplexer board. The other major component of the current sensor board is the burden resistor. Each current sensor requires a burden resistor (R_M) between the values of 60Ω and 275Ω. This resistor is used to determine the current proportional to the Hall Voltage using the equation:

$$I = \frac{V_H}{R_M} \tag{2}$$

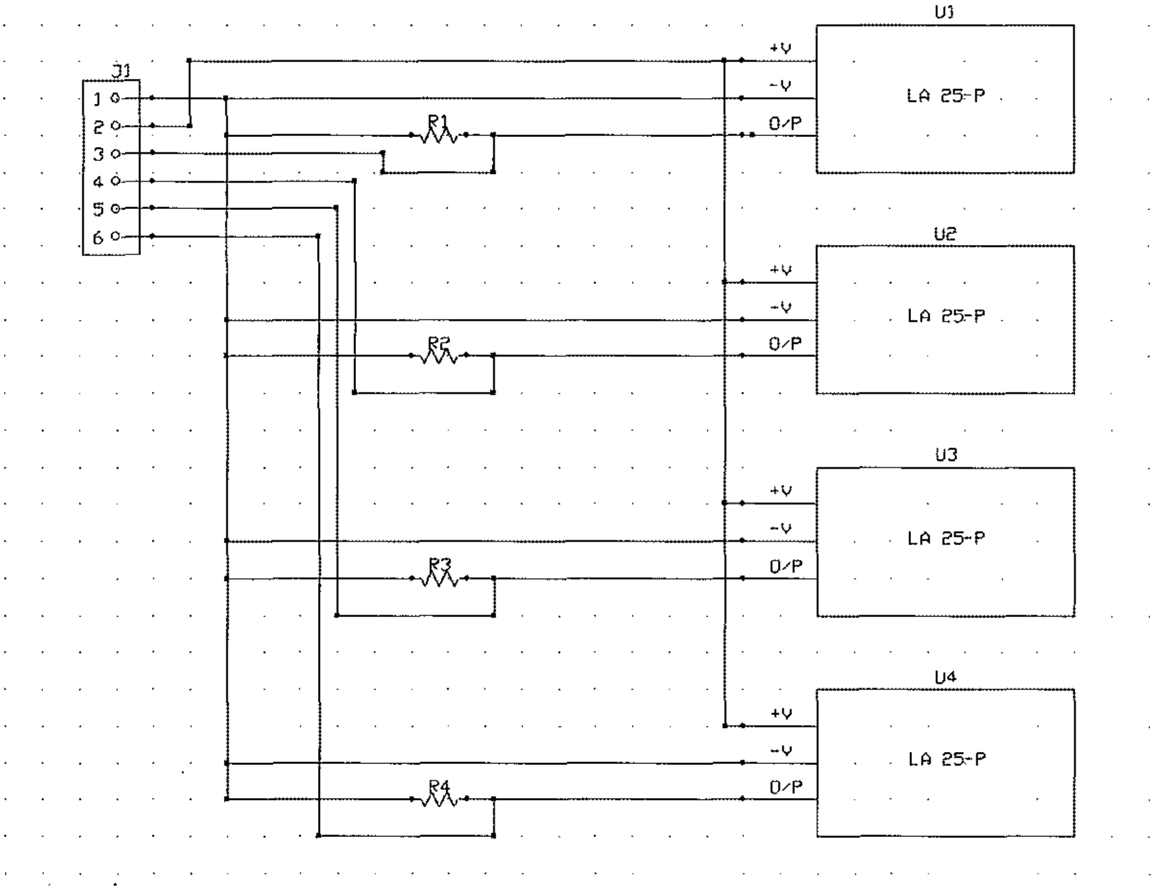


Figure 5.2 Current Sensor Board Schematic

5.1.2 Multiplexer Boards

The next PCB board of the fault detection system is the multiplexer board. This board incorporates several components used to collect the monitoring data. The first component of the multiplexer board is the voltage regulator. This device is used to convert the +24V DC power supply into the DC supply required for the on-board components. The schematic of the voltage regulator is shown below in Figure 5.3. From this we see that the only external circuitry of the voltage regulator are a few capacitors used to eliminate noise between the power and ground lines.

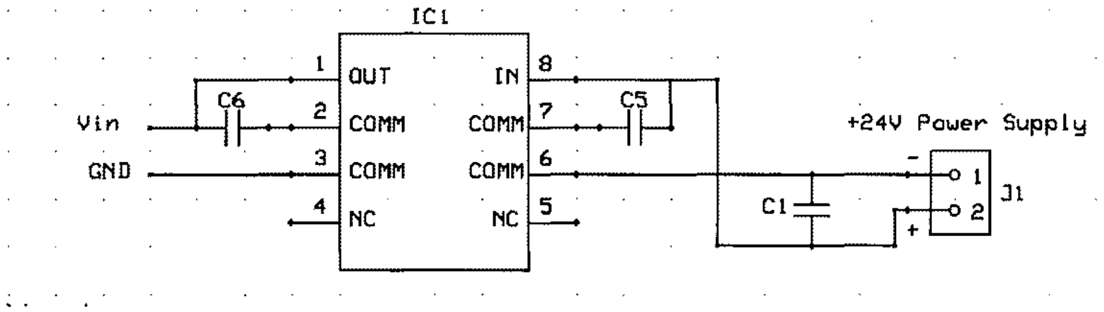


Figure 5.3 Voltage Regulator Schematic

The next component of the multiplexer board is the 1x16 multiplexer. This device is capable of multiplexing up to sixteen individual inputs with the use of four digital select lines and one analog output. The pin out of the multiplexer is given in Figure 5.4. Here V_{dd} is the supply voltage input and V_{ss} is ground. Pins A, B, C, and D are the digital select lines used to choose the channel to be read. The output of the selected channel is read from the Common In/Out pin and the Inhibit is permanently set to low.

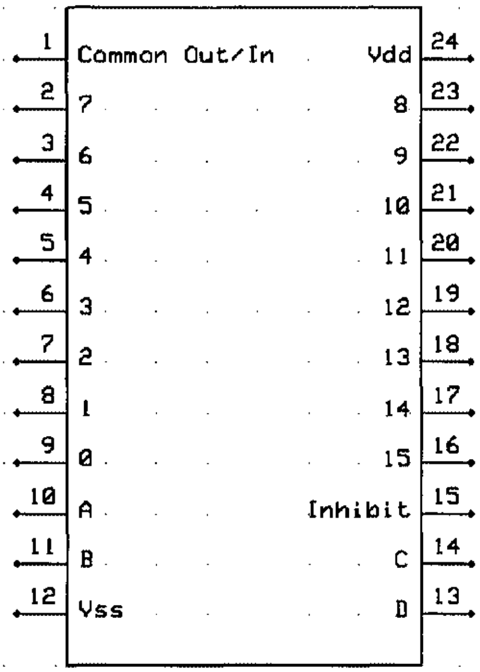


Figure 5.4 Multiplexer Pin Out

The final component of the multiplexer board is the combined voltage measurement. This value is obtained from the combiner comb and thus carries no current. However, the photovoltaic tracker system could reach a maximum output of 1000V. Therefore, the combined voltage must be scaled down and isolated to prevent shortage to the PLC. The voltage input is scaled by a factor of one hundred using a voltage divider. This is necessary since the inputs of the PLC have a maximum input of 10V. The output of the isolated components is then connected to an analog input of the PLC to be analyzed. The schematic of the isolated voltage unit is given below in Figure 5.5.

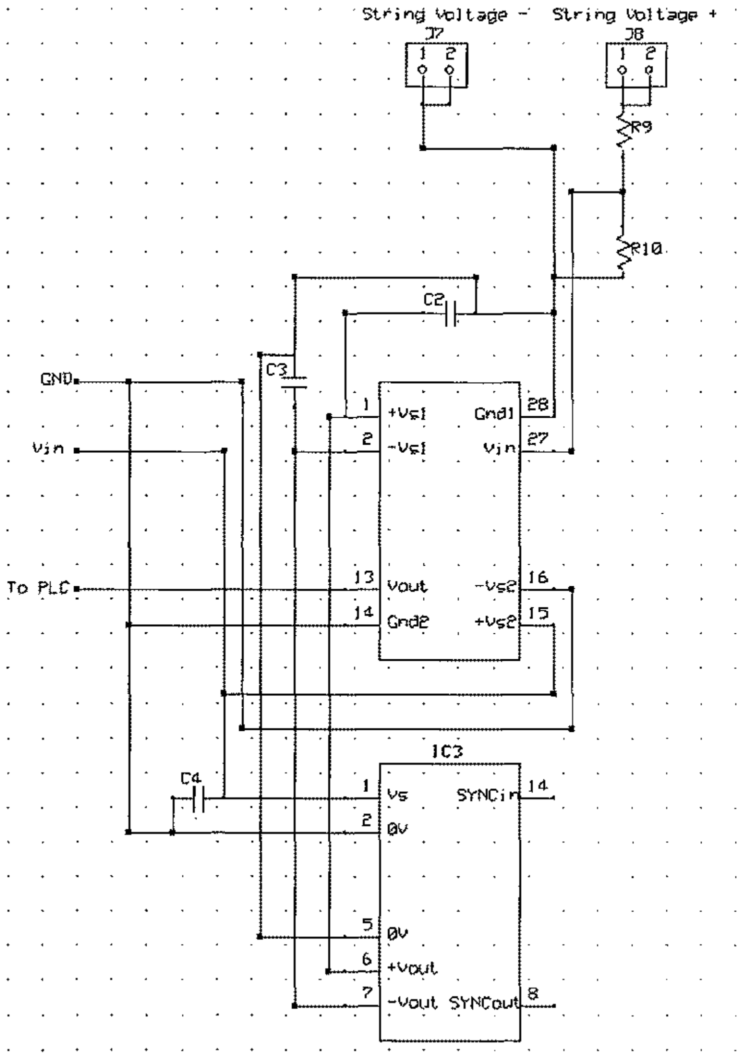


Figure 5.5 Isolated Voltage Measurement Schematic

5.2 Printed Circuit Board Design

5.2.1 Current Sensor Boards

Following the schematic design, the next step of the design process is the development of the printed circuit boards (PCB). All PCB design work was completed with the free-ware *ExpressPCB*. The current sensor board PCB required a special layout to allow for integration with the PV fuse panel. The boards were two layers and had to be cut to fit together universally for easy system expansion. The components also had to be oriented to eliminate any interference between the board and the combiner components. Therefore, the only circuit components soldered on the top layer of the board are the current sensors. The current sensors and connectors are through-hole devices while all other components used are surface mount. A section of current sensor board can be seen below in Figure 5.6. This image shows the footprint of one sensor and the associated external components. Here the red traces represent the top layer, green traces represent the bottom layer, and yellow markings represent the silk screen layer. The traces have been increased on the current sensor board to 0.025" to safely carry the 24V power supply. The 0.025" trace is capable of carrying up to 1.0A of current while the default trace width of 0.010" is only rated to carry 0.3A of current.

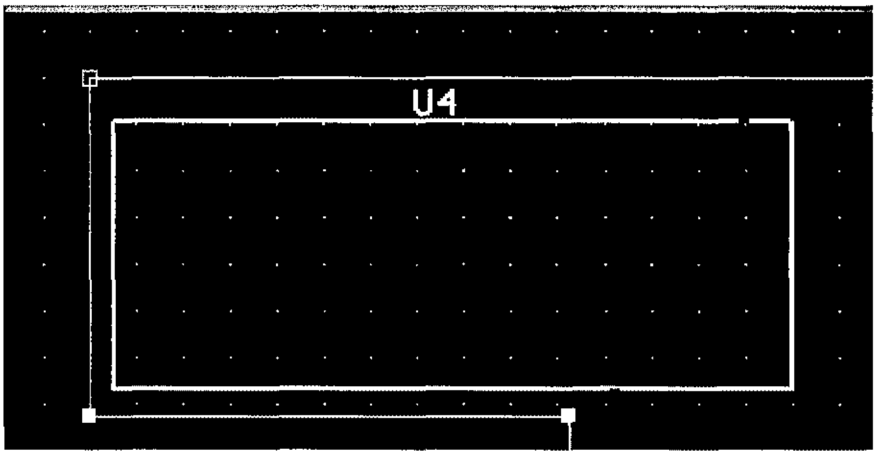


Figure 5.6 Current Sensor Board PCB: Single Sensor Footprint

5.2.2 Multiplexer Board

The PCB design for the multiplexer board is much more complex than that for the current sensor board. Like the current sensor boards, the multiplexer board is a two layer board. However, all of the components had to be mounted to the top surface of the board to enable easy access inside of the control panel. All of the components used were surface mount devices with the exception of the connectors. The board was also organized to facilitate easy installation and minimal wiring. Each of the three major components of the board were separated to easily distinguish the functions of the parts. The first section of the multiplexer board is the voltage regulator unit and the PCB design can be seen in Figure 5.7. From this image we see that the voltage divider unit has been grouped together on the board. The 24V DC power connector has been placed on the edge of the board for easy wiring at installation. The traces for all power lines containing 24V DC have been set to 0.025" to safely carry the increased power. All remaining traces have been left to the 0.010" width as the multiplexing and isolation components only draw approximately 50mA of current.

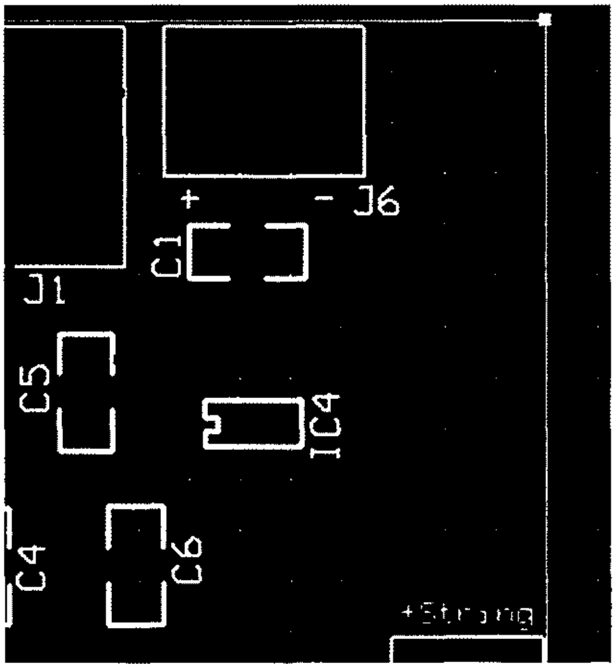


Figure 5.7 Multiplexer Board PCB: Voltage Regulator

The next section of the multiplexer board PCB is the multiplexing unit. The multiplexer and associated components consume the majority of the multiplexer board. All of the current sensor board input connectors have been places along one side of the board. This allows for easily installation and eliminates wires crossing the board within the control panel. The current sensor connectors have also been placed in numerical order despite conflict with the multiplexer pin layout. Such conflicts resulted in the use of several vias to make the connectors from the current sensors correspond with the appropriate numbered channels. The digital select lines and analog output of the multiplexer are then sent to the multiplexer with the use of a screw terminal.

The final section of the multiplexer board PCB is the isolated voltage measurement unit. These components were placed on the board to allow for easy wiring from the combiner components to the board. The string voltage input connections required two separate screw terminals since components on the market today are only rated for a maximum of 600V. Since this rating is only for the distance between the two terminal pins, this problem was solved by using two identical terminals for both positive and negative inputs. To ensure proper installation wiring the two pins of each terminal were wired together so that the pin used to input the voltage does not have to be specified. The connectors are also labeled on the board so the negative and positive voltage inputs are not confused.

5.3 Combiner

A unique feature of the fault detection system designed in this thesis research is the combiner box integration. This is accomplished by utilizing the existing fuse panel used in photovoltaic tracker applications. The closed-loop current sensors also aid in this combiner integration by not interrupting the flow of power through the photovoltaic strings. In this thesis a combiner comb which passes through the current sensors and locks into the fuse panel was developed. This combiner comb can be seen below in Figure 5.8. The component is manufactured from aluminum and cut to precisely fit into the fuse blocks. The teeth of the comb are size accordingly to handle the maximum current of 320A from the sixteen photovoltaic strings. The other component of the combiner system is the ground bus bar which simply consists of an aluminum bar with a sixteen pin screw terminal rail. Both combiner modules use a six gauge lug to send the combined photovoltaic strings to the inverter.

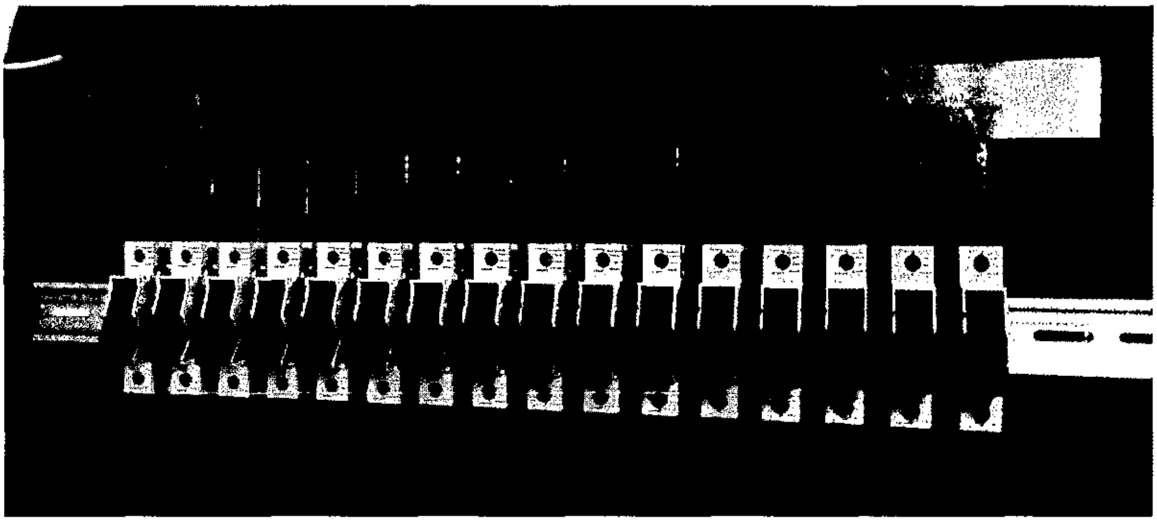


Figure 5.8 Combiner Comb with PV Fuse Panel

5.4 System Assembly

Once the design phase of all of the circuit boards and components was completed, the system was assembled. Each board required a specific method of assembly due to the usage of both through-hole and surface mount components. The surface mount components for both the current sensor boards and multiplexer board were assembled first. This was accomplished with the use of liquid solder paste and a surface mount reflow oven. The next phase of assembly for both boards included assembly of the through-hole sensors and connectors. The entire assembly process for all of the boards takes less than an hour and can be shortened with the aid of automatic machinery. The completed current sensor board can be seen below in Figure 5.9. The remaining steps of the assembly process include integrating the multiplexer and current sensor boards with the combiner comb and fuse panel.

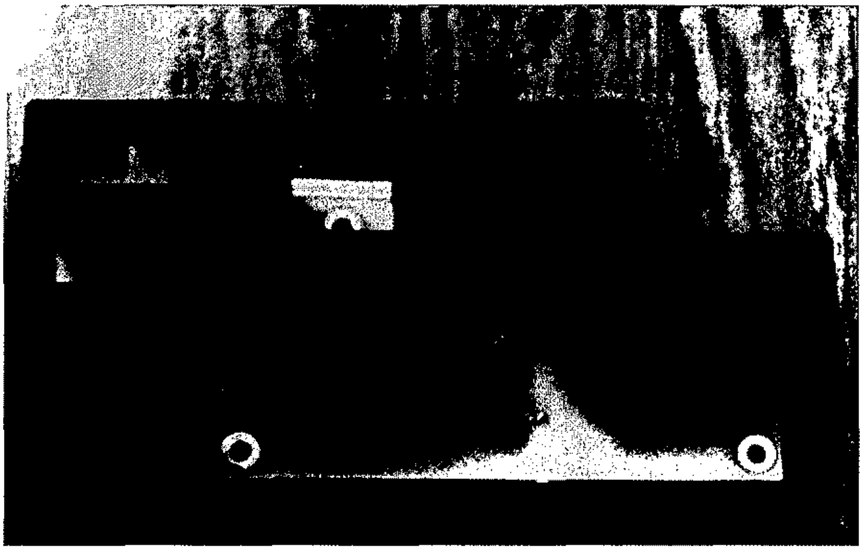


Figure 5.9 Assembled Current Sensor Board

5.5 PLC Programming

An additional key feature of the system is the usage of the PLC to handle all data acquisition and analysis. The PLC used in this application is the Simatic S7-1200 manufactured by Siemens. This PLC has fourteen digital inputs, two analog inputs, and ten digital outputs [5]. The S7-1200 PLC and the associated inputs can be seen in Figure 5.10. The software used to program the PLC is Siemens *Totally Integrated (TIA) Portal* which enables the user to program the field PLCs, master PLC, and all HMIs. The photovoltaic tracker monitoring system requires a PLC program which will read the current sensor outputs from the multiplexer as well as the voltage measurement from the combiner.

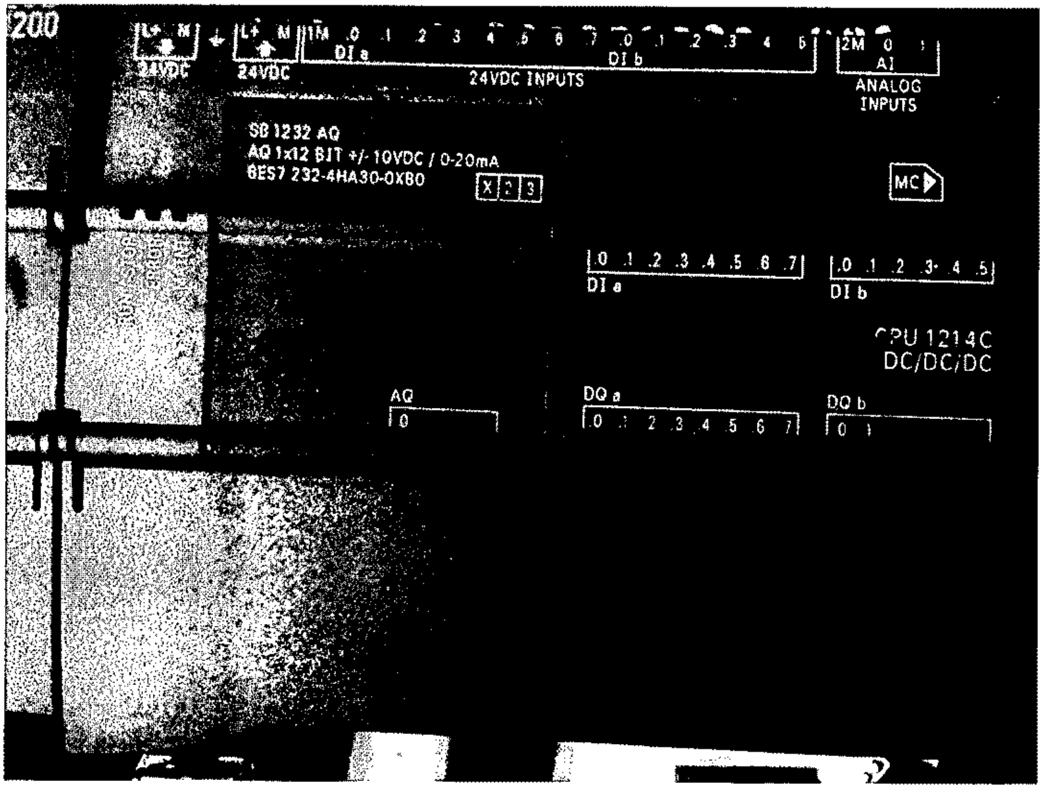
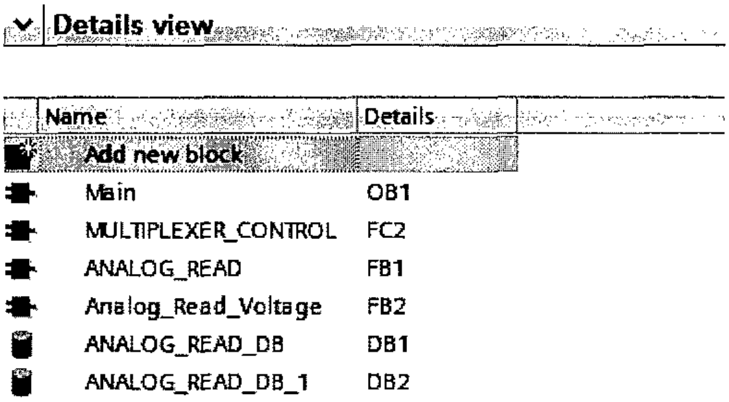


Figure 5.10 Siemens Simatic S7-1200 PLC

The first step of writing the PLC program is to set up the devices and networks for which the program will communicate with. All system parameters such as the date, time, and IP (internet protocol) addresses of the devices are assigned. PLC programming uses a type of graphical language known as ladder logic. This language is broken down into program blocks which serve different functions. The next step of the programming process is the setup of the program blocks. The monitoring program contains four different blocks which include the Main block, Multiplexer Control block, Analog Read block, and the Analog Read Voltage block. These program blocks can be seen below in Figure 5.11 along with the associated program block type. The Main block is an Organizational Block (OB), the Multiplexer Control block is a Function (FC), and the

Analog Read block and Analog Read Voltage blocks are both Functional Blocks (FB). The Function and Functional Blocks are placed within the Operational Block which serves as the Main program.



Details view

Name	Details
Add new block	
Main	OB1
MULTIPLEXER_CONTROL	FC2
ANALOG_READ	FB1
Analog_Read_Voltage	FB2
ANALOG_READ_DB	DB1
ANALOG_READ_DB_1	DB2

Figure 5.11 PLC Program Blocks

The first part of the program is the Multiplexer Control Function which is used to obtain the data from the multiplexer and current sensors. This block contains a 1Hz clock pulse which is used to alternate which channel of the multiplexer is to be read. The program then reads each of the channels from 0 to 15. However, the four digital select lines used to choose the channels are addressed using Boolean logic. Therefore, the program must request data using that addresses 0000 to 1111. This is accomplished by using a *word* to obtain data from the channels with the addresses *q0.0* to *q0.3*. When the specified channel is selected the PLC reads the output from the analog input of the multiplexer.

The next part of the program is the Analog Read Function Block which is used to convert the current sensor outputs from the *word* format to a usable *integer*. This is accomplished by first acquiring the data and then normalizing and scaling the value between 0.0 and 10.0. Since the output of the current sensor is a voltage, we must next calculate the proportional current. This is done with the use of the equation:

$$I = \left(\frac{sensor\ output}{R_M}\right)1000 \tag{4}$$

Here the R_M is the burden resistor value and 1000 is obtained from the turn ratio of the closed-loop current transducer. Once all of the values have been obtained, scaled, and converted to current measurements, the values are then stored within the Analog Read Data Block.

The final part of the program is the Analog Read Voltage Function Block. This block is simply used to read the analog input of the combined string voltage. Once obtained from the multiplexer board, the value is then normalized and scaled to a value between 0.0 and 10.0. The values are then multiplied by 100 to correct for the voltage divider used on the multiplexer board. The final voltage measurements are then stored within the Analog Read Voltage Data Block.

CHAPTER 6

TESTING AND ANALYSIS OF MONITORING SYSTEM

6.1 System Testing

In order to determine the validity of the photovoltaic tracker monitoring system, testing and analysis was necessary. The testing of the monitoring system was very similar to that previously utilized to test the variety of current sensors. Several instruments were used in the experimental setup of the testing process. Such instruments include a 24V DC supply, a high current power source, a voltage source, a resistive load, and a multimeter. The previously obtained LEM LA 25-P current sensor testing data was used as a control during the testing of the fault detection system. This data has been provided in Chapter 5.

Once the system was assembled, the first step of the testing procedure is the attachment of the 24V DC power supply to the inputs of the multiplexer board. Next the high current power source was used with the resistive load to simulate the photovoltaic strings. The simulated strings were simply run through the closed-loop sensors for preliminary testing procedures. The digital select lines were then turned on or off using the voltage source to simulate the PLC control. Once a channel was selected, the analog output of the multiplexer was then read with the voltmeter to ensure the proper values were measured by the currents sensors. Finally, the voltage measurement was tested by applying a voltage to the inputs on the multiplexer board and measuring the output with the voltmeter. This testing procedure was used to confirm that the monitoring system design was functional and accurate. Further testing will be done in the future to fully integrate the system with the combiner features as well as the PLC.

6.2 System Cost Analysis

While the reliability of the monitoring system is a very important factor, we must also take into consideration the cost of investment. Several measures have been taken in the design process to reduce the production cost of the system. Such measures include using two-layer PCB boards as well as only using components which are readily available at reduced prices. Majority of the component used in the monitoring system are available in bulk from Digikey which makes the ordering process simpler and cheaper. A cost analysis has been performed for 1 photovoltaic tracker monitoring system and 250 photovoltaic tracker monitoring systems. This cost analysis is given below in Table 6.1.

Table 6.1 Cost Analysis for Manufacturing 1 Monitoring System vs. 250 Monitoring Systems

Component	**1 System**	**250 Systems**
PCB Boards	$310.35	$5952.76
Current Sensors	$309.60	$52000.00
IC Chips	$33.21	$4786.17
Resistors/Capacitors	$17.01	$221.30
Combiner	$44.00	$11000.00
Connectors	$30.01	$3001.07
Price Per System	**$744.18**	**$307.84**

From this table we see that the cost of each system is extremely high for a single system but is reduced by over 50% when produced in mass quantities. These could still be significantly reduced by manufacturing the PCB boards and combiner system through a larger company. The largest cost of the monitoring system lies in the current sensors which unfortunately cannot be further reduced. Closed-loop sensors are difficult to manufacture and thus have a high price tag. To reduce this cost in the future, an alternative to the closed-loop current sensors could be considered.

CHAPTER 7

CONCLUSIONS

Rising energy consumption and costs of fossil fuels are rapidly becoming a major issue in today's society. Renewable energy resources are the most effective way of reducing the impact of fossil fuels and aiding in increased energy demands. One of the most effective renewable energy resources available is solar energy. While solar energy is manufactured in a variety of ways, the most popular method is photovoltaics. With the currently low efficiency of solar modules, larger fixed-panel photovoltaic systems and tracking photovoltaic systems are being utilized.

Photovoltaic tracker systems are the preferred technique of increasing solar energy efficiency since land and space is saved in the process. However, tracking systems are more expensive and thus need a form of monitoring to ensure the highest level of productivity. Currently, inverters are the only practice of monitoring the power produced by photovoltaic systems. Unfortunately, inverters account for around 50% of faults within the photovoltaic system making this an unreliable method of monitoring.

A unique fault detection and combiner system has been developed to optimize the yield of photovoltaic tracker systems without relying on the inverters. This design applies the Hall Effect and closed-loop sensors as a means of indirectly monitoring the current of each photovoltaic string. The components used are robust and readily available to ensure effective application for many years. The monitoring system also takes advantage of existing photovoltaic tracker devices to successfully integrate the combiner system.

While the fault detection system developed in this thesis accomplishes the goals, improvements can still be made in the future. The cost of each system is relatively high and should be reduced as new components are developed. The monitoring system is also very large and should be minimized to directly reduce the size of the photovoltaic control panel.

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