MAXIMUM POWER POINT BASED SOLAR TRACKER

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Undergoing a thesis research is a daunting task, about the difficulty of which I had little idea when I started off with it. Right from the beginning till the end; the whole process of selecting the topic, gathering information, accessing sources, analyzing the assembled data and info, drawing results and distilling conclusions cannot be done without proper guidance of the professionals in the field, the advisory committee and most specially the thesis supervisor.

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I would specially thank all of my friends who stood by me through days that weren't so sunny and helped me sail through the rough tides. I am at loss to find words to thank my parents who have sacrificed and prayed every day to help me get the best in life.

Last but not the least; the dark stretches of a distressed heart are illuminated by none other than the light emanating from the sole source of all knowledge and wisdom – Allah Almighty. He had been a Supreme Guide and a Best Friend all along.

ABSTRACT

This project focuses on the enhancement of electric energy produced from PV solar panels as a result of solar tracking. The concept of solar tracking is that by facing the solar panels towards the sun results in enhanced solar power gathered during the entire day. There are multiple options available for solar tracking such as chronological, sensor based and power based. The tracker that has been developed uses maximum power point strategy for solar tracking .The development of the tracking system is based on finding the max power point orientation of a PV solar panel at which max power is delivered. Two techniques for monitoring “Real-time power” have been demonstrated.

The tracking system has many advantages in relation to similar devices. It is intelligent in a way that it performs real-time power monitoring and has the ability to store data and improve behavior based on previous tracking history. The efficiency of the solar tracker includes its capability to compensate clouds and make adjustments according to seasonal changes.

Furthermore the control unit for tracking has been tested on a wide variety of single axis tracking platforms. The final result increases the energy return of the soar modules by 35-40 % on average, and up to 55 % in summer months. Furthermore the tracker is very useful for the Pakistani market since it is user friendly and requires no input from the user.

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List of Symbols

English letters:

P	Power
V	Voltage
I	Current
T	Absolute temperature
I_o	Saturation current
k	Boltzmann constant
G	Incident light intensity
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage

Acronyms:

P&O	Perturb and Observe.
MPP	Maximum Power Point.
PWM	Pulse Width Modulation.

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Chapter 1- INTRODUTION

One of the most fundamental problems facing the world today is the energy crisis. This problem has resulted from the increase of demand for electrical energy and high cost of fuel. Solar power is an alternative technology that will hopefully lead us away from the petroleum dependent energy sources.

Solar energy is created deep within the core of the Sun. It is here that the temperature (15,000,000° C; 27,000,000° F) and pressure (340 billion times Earth's air pressure at sea level) is so intense that nuclear reactions take place. This reaction causes four protons or hydrogen nuclei to fuse together to form one alpha particle or helium nucleus. The alpha particle is about 0.7% less massive than the four protons. The difference in mass is expelled as energy and is carried to the surface of the Sun, through a process known as convection, where it is released as light and heat. Energy generated in the Sun's core takes a million years to reach its surface. Every second 700 million tons of hydrogen are converted into helium ashes. In the process 5 million tons of pure energy is released; therefore, as time goes on the Sun is becoming lighter.

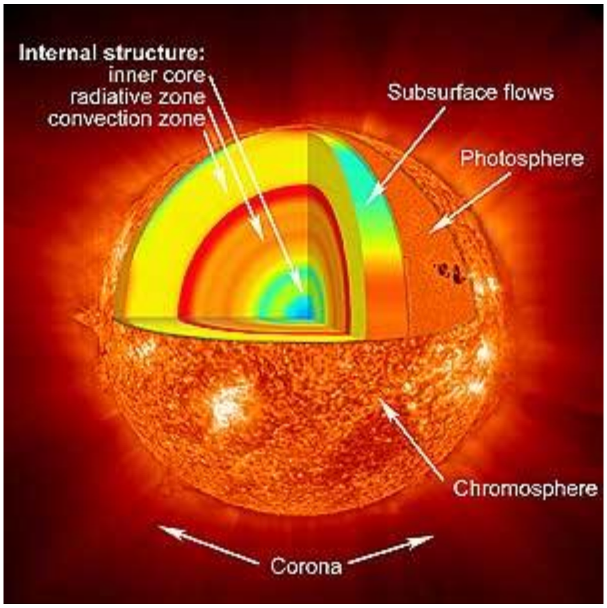


Figure 1. Dissection of Sun

Prominences are immense clouds of glowing gas that erupt from the upper chromospheres. The outer region of the corona stretches far into space and consists of particles traveling slowly away from the Sun. The corona can only be seen during total solar eclipses.

The Sun appears to have been active for 4.6 billion years and has enough fuel to go on for another five billion years or so. At the end of its life, the Sun will start to fuse helium into heavier elements and begin to swell up; ultimately growing so large that it will swallow the Earth. After a billion years as a red giant, it will suddenly collapse into a white dwarf -- the final end product of a star like ours. It may take a trillion years to cool off completely.

The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet.

Earth's land surface, oceans and atmosphere absorb solar radiation, and this raises their temperature. Sunlight absorbed by the oceans and land masses keeps the surface at an average temperature of 14 °C. By photosynthesis green plants convert solar energy into chemical energy, which produces food, wood and the biomass from which fossil fuels are derived.

The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. An Exajoules (EJ) is approximately equal to 10^{18} Joules. In 2002, this was more energy in one hour than the world used in one year. Photosynthesis captures approximately 3,000 EJ per year in biomass. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined.

It appears that solar, wind or biomass would be sufficient to supply all of our energy needs; however, the increased use of biomass has had a negative effect on global warming and dramatically increased food prices by diverting forests and crops in to biofuel production. As intermittent resources, solar and wind raise other issues.

Solar energy can be harnessed in different levels around the world. The apparent yearly path of the Sun through the stars is called the ecliptic. This circular path is tilted 23.5 degrees with respect to the celestial equator because the Earth's rotation axis is tilted by 23.5 degrees with respect to its orbital plane.

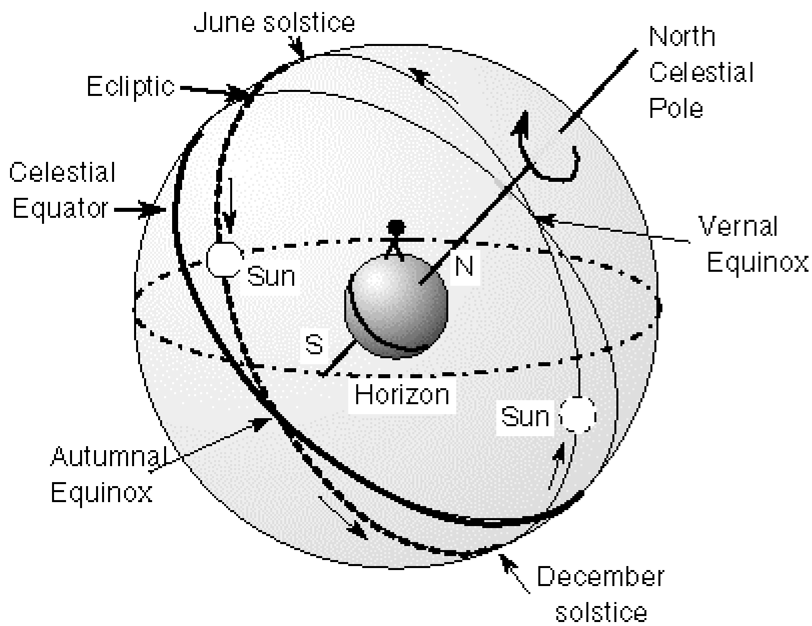


Figure 2. Path of Sun

Depending on a geographical location the closer to the equator the more "potential" solar energy is available.

The amazing thing about solar power is that all the electricity is generated from the material of the solar panels and the energy from the sun. It is one of the most rapidly growing sources of alternative energy in the world. Fortunately Pakistan receives large amounts of solar energy (5-5.9 Wh/m^2) which can be utilized to make clean, economical and reliable electricity for the future generations. The cost of solar panels is one of the biggest obstacles in using solar power. Solar panels are measured in terms of power (Watts), so if their power output is increased, this as a result reduces the net cost. This cost can be reduced by using a solar tracking system which is a means of keeping the panels facing the sun (at optimum angle) giving maximum power output throughout the day.

A single axis solar tracker will increase the energy return from solar modules by 35-40 % averaged over a year, depending upon location and up to 50 % in summer months. The tracking system can greatly reduce the cost of solar energy by reducing the number of solar modules required per watt. The major problem with solar panel technology is that the efficiencies for solar power systems are still poor and the costs are not competitive, in most cases, to compete with petroleum energy sources. The goal is to design a Tracking system which is self powered, robust, does not require any input parameters and can boost output power by 30-40 %.

This project focuses on the optimization of the electric energy production by photovoltaic cells through the development of an intelligent sun-tracking system. The developed tracking system is innovative in relation to the usual conventional systems.

The report is arranged into 7 chapters. Chapter 1 is this, introduction chapter, and it introduces the basic dissection of sun and the overview of its energy and brief about the project, chapter 2 deals with the background of the technical work done in this project. Then chapter 3 describes the techniques for the implementation of the project along with the electronic part description of the project. Chapter 4 is an overview of techniques and part selection theory, whereas in chapter 5 hardware design is discussed along with Pro-E analysis of hardware model to show the strength of the model. Chapter 6 is the Software portion of the report which includes the simulation and code algorithm, chapter 7 deals with the result and conclusions based on different sort of analysis and test. Chapter 8 is the future recommendations which can be done by others in near future with research.

Chapter 2- BACKGROUND

2.1 Introduction

This chapter deals with the brief overview of different aspects of the project like how the solar power is gained and how the efficiency of achieved power can be increased or dereased. It also describes different phenomenas on which project theory is based along with the description of product involved in the whole process.

2.2 Technical Background

2.2.1 Solar Power Fundamentals

Solar panels are mainly made out of semiconductor material, silicon being the most abundantly used semiconductor. The benefit of using semiconductor material is largely due to the ability of being able to control its conductivity whereas insulators and conductors cannot be altered. The electrons of the semiconductor material can be located in one of two different bands: the conduction band or the valence band.

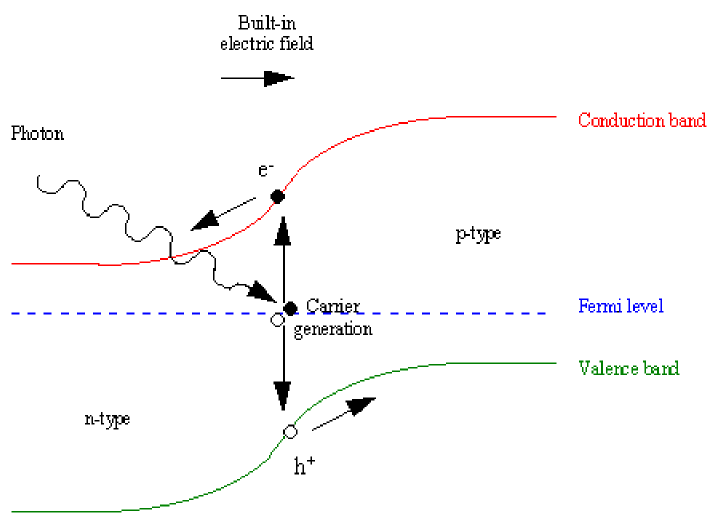


Figure 3.A photon moves an electron from valence band to conduction band

The valence band is initially full with all the electrons that the material contains. When the energy from sunlight, known as photons, strikes the electrons in the semiconductor, some of these electrons will acquire enough energy to leave the valence band and enter the conduction band. When this occurs, the electrons in the conduction band begin to move creating electricity. As soon as the electron leaves the valence band, a positively charged hole will remain in the location the electron departed. When this occurs, the valence band is no longer full and can also play a role in the current flow. This process basically describes how Photovoltaic (PV) systems function. However, PV systems further enhance the rate at which the electrons are sent into the conduction band through the process of doping.

2.2.2 Efficiency of Solar modules

Solar power would be the leading source of energy if it were able to efficiently extract a majority of the energy delivered to the earth from the sun on a daily basis. On the equator at noon, 1000 Watts/m^2 of sun energy touches the ground. Unfortunately only about 20 percent of this power can be transferred into usable energy. This inefficiency is directly related to the percentage of photons that are absorbed. The electrons in the semiconductor material will only jump into the conduction band if they absorb a photon. The photons can either be absorbed, reflected, or can even pass right through the semiconductor. There is an obvious loss of electric potential when the photons are reflected off the semiconductor material. To reduce the percentage of reflected photons, an anti-reflective coating is usually put on the semiconductor, which will decrease the number of reflected photons increasing the total number of photons that will become absorbed.

The most critical parameter that affects the power output of the solar panel is solar irradiance. As power is the product of current and voltage, the following equations define a relationship between open circuit voltage and short circuit current.

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_O}\right) \quad (1)$$

$$I_{SC} = bG \quad (2)$$

Where I_o is the saturation current, q is the electronic charge, k is the Boltzmann constant, T is the absolute temperature, G is incident light intensity, and b is a constant, depends on the properties of the semiconductor junction, the orientation, geometry detector and the size of the collector area. As time goes on, newer manufacturing techniques and designs will prove these solar panels more efficient and less costly in future years. Rather than focusing on the issues relating to the design and semiconductor physics behind the solar panels themselves, this project will focuses more on the increasing the output of the solar panels. A solar panel's output varies depending on certain ambient weather conditions such as temperature, illumination, how clear the sky is, so on and so forth. The task at hand is to design a device that will extract the maximum amount of power from the solar panels, regardless of how efficient or inefficient the solar panels may be.

2.2.3 Voltage-Current (V-I) Characteristic

Extracting the maximum amount of power from the solar panel is difficult due to the nonlinearity of the Voltage-Current (V-I) characteristic. Fig.4. shows the VI characteristic for a typical solar panel.

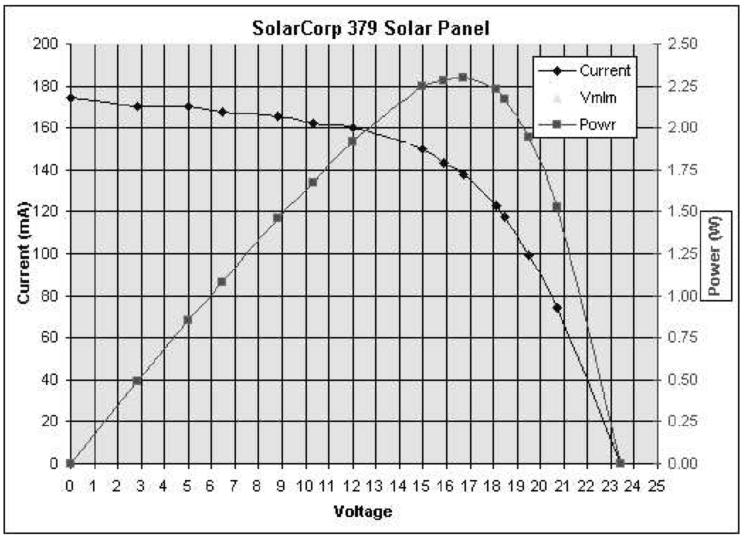


Figure 4.Characteristic VI curve of a solar panel

As it can be noticed, the voltage to current relationship is not linear, which makes it a little more difficult to determine the maximum power point. The maximum power point on a linear curve would occur at the midpoint of the V-I characteristic.

However, in the case of a nonlinear relationship, the power needs to be determined by calculating the voltage to the current. To get the maximum power from the solar panel, the solar panel must always be operated at or very near the point where the power curve is at a maximum, its peak point. However, this operating point will constantly change due to the constantly changing ambient conditions. In fact, the temperature and other affects such as irradiance alter the V-I characteristic changing the operating point that would allow us to pull out the maximum amount of power. As a result, we need to constantly track the power curve and keep the solar panel oriented where the maximum amount of power would be achieved. Irradiance is a characteristic that deals with the amount of sun energy reaching the ground. The irradiance reaching the earth in ideal conditions is 1000W/m^2. However, this value is altered significantly depending on where you are located geographically, the angle of the sun, and the amount of haze or cloud cover preventing all of the suns energy from reaching the ground. Since solar panels run strictly off the energy emitted from the sun, their output is affected by the changing irradiance. The Fig.5 below demonstrates the affect irradiance has on the output of solar panels.

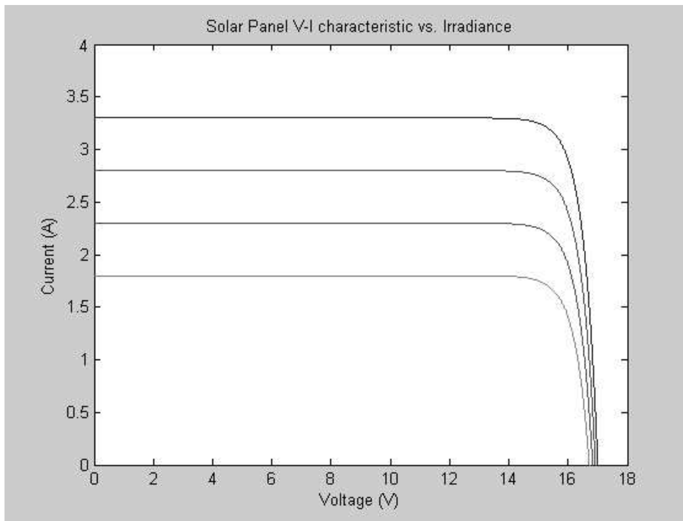


Figure5. Solar panel VI characteristic vs. Irradiance

The higher the solar irradiance at a particular point, the greater will its Max power point be. The Max power point (MPP) is a point on the knee of the curve, where the product of V x I maximizes.

Temperature also has an effect on the performance of a solar panel as can be shown in Figure 4 where the MPP is decreased slightly due to an increase in energy.

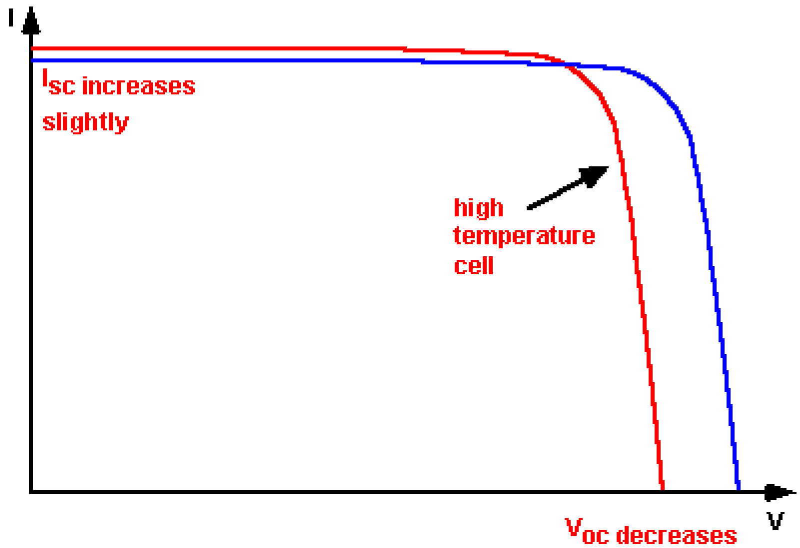


Figure 6.Solar panel VI characteristic vs. temperature

As shown in Fig.6 above, the output does in fact increase with decreasing temperature. There are many factors in determining why this occurs. A huge reason is due to the electron and hole mobility of the semiconductor material. As the temperature rises, the electron and hole mobility in the material decreases significantly. The electron mobility for a Silicon semiconductor solar panel will decrease from 1700 cm^2/volt-sec at 27C to 440 cm^2/volt-sec at 227C where the hole mobility will decrease from 600 cm^2/volt-sec at 27oC to 200 cm^2/volt-sec at 227C.

High temperature also causes the band gap energy of the semiconductor material to increase. The photons from the sun provide the electrons in the valence band of the semiconductor with the energy to leap over the band gap into the semiconductor material. With larger band gap energy, the electrons will require more energy from the photons in the sun to reach the conduction band.

As a result, fewer electrons will reach the conduction band giving us a less efficient solar cell. These changes in temperature and irradiance make the V-I characteristic near impossible to predict or control. The only thing we have control over is the operating point of the solar panel. Without control over this operating point, the output of the solar panels will be very unpredictable resulting in an even more inefficient solar power system.

2.2.4 Insolation Levels

Insolation levels are a measure of how much sunlight energy is delivered to a square meter over a single day. The sun's energy is most powerful at the equator at solar noon, or when the sun is directly overhead. The sun's energy will be dramatically decreased by the earth's atmosphere. Energy will also be lost because of the angle of reflection against the solar panel. The sun's energy is strongest when it is straight overhead, where the earth's atmosphere, and the solar panel's reflection has the least affect. Insolation levels measure the amount of energy in watt-hours for a square meter over a single day in Kwh/m^2/day. Insolation level units are not always stated, and can be seen as a ratio. Therefore we will intentionally leave the units off. The sun's energy varies as the sun moves from the horizon to directly overhead. The insolation level is an equivalent solar energy level. The sun's energy at the equator at solar noon is equal to 1000 watts per square meter. In effect, we are finding the amount of equivalent hours the sun has put out 1000 watts per square meter. Although the sun may have been shining at 500 watts per square meter for 8 hours, there is only 4 equivalent hours of 1000 watts per square meter. Insolation levels give an easy way to compare sunlight energy levels between locations as well as find typical solar and battery requirements for a given location. An insolation level between one and two is considered to be low. Four and five are considered to be moderate and seven to eight is high.

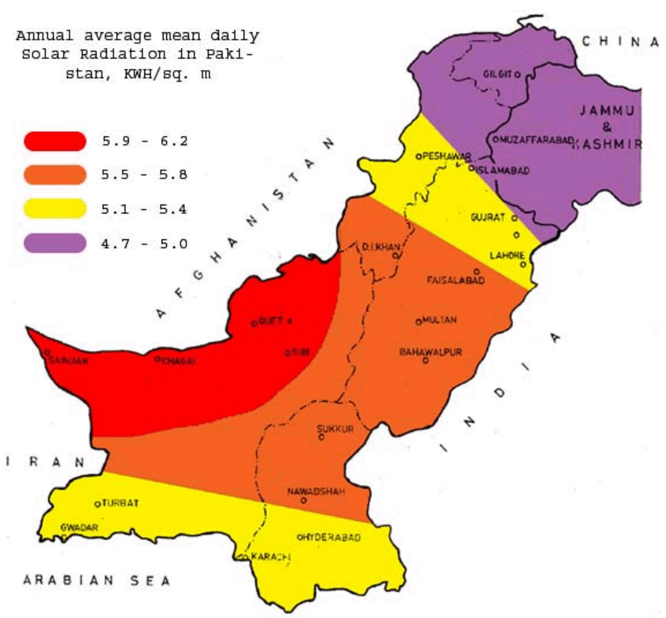


Figure 7.Solar Insolation levels in Pakistan

It is often common for solar panels to be backed up by a generator to supply power for the winter months. The solar panels can be used more efficiency by angling them towards the sun. Sun tracking mounts designed for solar cells exist now. These self powered mounts point the solar cells directly to the sun to get the most amount of solar power. Of course this also uses some of the energy from the solar cell itself. The solar panel is not rated in just efficiency but instead how many watts it can produce. The solar panel have been provided with is 50W. If this panel is producing 50W under ideal conditions ($1000W/m^2$) then we can expect to draw four times as much as that per day in place where sun intensity is high since the insolation level is $4000W/m^2$. Therefore it can be expected to store an equivalent of 50W for four hours, or a more standard form to state this is 200W of power for one hour or 200Wh. The storage of this power depends greatly on the sun. It can be expected the most amount of power while the sun is around solar noon. Before and after solar noon, lower power levels can be expected. Sunlight energy around the world varies considerably. The closer to the equator, the more sunlight energy is available throughout the year. This is the most ideal place for solar electricity. Other places, such as London have very low yearly averages and are not practical to use solar technology. Remote locations that are far away from power grids also provide a practical use for solar technology.

2.2.5 Other factors affecting Solar panel performance

Other variables that one may choose to observe are wind speed and direction, UV-radiation, the spectrum of sunlight, and the air moisture level.

The wind speed plays an important role in determining module temperature, since convective heat losses at the surface of the module are much larger at high wind speeds. Wind direction has to be related to module placement to determine how strong this effect is at any given time. In the results section of this report, a simple test has been performed with varying wind speeds. It confirms the fact that at higher wind speeds, the Power output increases slightly due to lower temperature of the solar panel.

2.3 Product Background

2.3.1 Customer requirements

Three of the most important customer requirements are cost, efficiency and reliability, and how much time is required to maintain the system. In order to increase the efficiency of photovoltaic panels, solar tracking systems have been developed. Regular mounted solar arrays do not optimally collect sunlight and arrays with tracking systems have been shown to increase power output by an average of 30%.

One of the main goals is for the array to have decreased power consumption, increased durability and lifetime, at a much lower cost to the customer. Some features planon incorporating to the design are maximum power output, microprocessor control during inclement weather conditions, and reduced cost. It was not decided whether to use a single axis system or a dual axis actively controlled system. The single axis allows reducing cost, decrease motor power consumption, and increase reliability/durability without significant loss of power generation due to longitudinal discrepancies. Using a dual axis system can increase costs, but could reduce maintenance by eliminating quarterly adjustments of the azimuth angle. Two options were under consideration for increased efficiency before making the final decision. The target customer for the product is anyone who wishes to decrease reliance on non-renewable sources at a minimum cost. This could be home systems of 1 kW or commercial systems up to 100 kW. A large system would use many separate tracking controls for separate photovoltaic arrays.

2.3.2 Product Analysis

In order to compare existing solar tracking systems following categories were evaluated: power requirements, tracking methods, cost, and number of axis, dynamic control method, and photovoltaic (PV) array size. From these different specifications we were able to see which methods had become industry standards, and which ones varied from company to company. The power requirements varied from 12-48VDC and 120VAC.

A detailed spreadsheet (Table 1) of products/designs that is similar in function or performance in order to gain a better understanding of which features distinguish the best products from the rest.

Model	Manufacturer	Power Req.	Tracking Method	Number of Axis	Dynamic Control	PV Size
ETATRACK active 1500	Lorentz	24VDC	Time-based operation	1	Linear Actuators	Up to 2.5kW
Davy Solatraka LD	Davy Industries	12-24VDC	Unknown	1	Linear Actuators	0.5kW
SP675/4150	Sunwise Pacific Sun Tracker	24VDC	Time-based operation	2	Linear Actuators	0.5kW
ST-8	Solenergy	12-48VDC	Active Sun-sensing operation	2	Linear Actuators	1kW
Power Tracker	Power Light	120VAC	GPS-controller tracking	1	Linear Actuators	1kW
TR-15	Watt Sun	24VDC	Active Sun-sensing operation	1	Linear Actuators	0.25kW
TOP Tracker	DEGER Energie	24VDC	Active Sun-sensing operation	1	Linear Actuators	1kW

2.3.3 Target Feature Set – Project Goals

We will be using Active Sun-sensing operation using sensors to maintain the most efficient E to W incident angle, to within two degrees of normal to the sun's rays. It will be controlling azimuth angle as well, again to within two degrees of normal.

Product will be completely self-sustaining to provide power in the event the grid power goes down. 12VDC system is used that can easily be run with common deep-cycle batteries.

The tracker will implement linear actuators and pulse width modulation to refine the movement of the PV array. The full swing of the array from east to west to take approximately ten minutes is estimated.

The design will attempt to provide an alternative to the expensive units already on the market. The basic price will be in the same vicinity as the expense of photovoltaic panels doesn’t change by more than 3%. However, the product will seek to reduce all other associated costs, without a reduction in efficiency.

It was desired to seek a design that is scalable for single home use to large commercial arrays. This will allow targeting a large number of possible consumers.

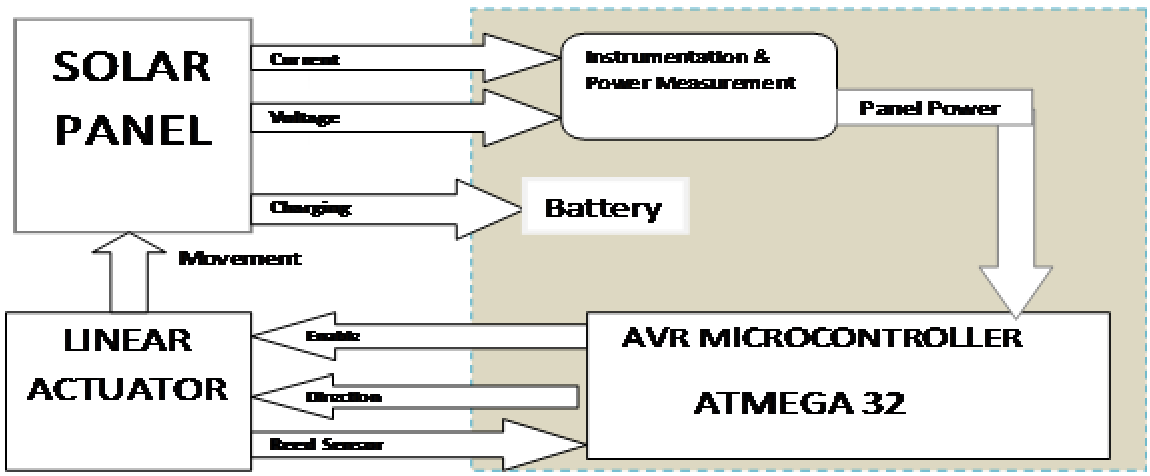
This will utilize a time-based backup for inclement weather conditions (clouds, rain, wind, etc.). This will override the active sensing to prevent wasting power through chasing.

Chapter 3- METHODOLOGY

3.1 Introduction

This chapter deals with the narrative of methods and phenomenas which can be used in solar tracking system and the method applied in the project, this description also includes the drawbacks of the different approaches. Mechanical description of the product, along with the ways to control it, is also explained in it. The Pro-E analysis and results on this mechanical design are described in chapter 5.

3.2 System Block Diagram



3.3 Implementation approaches

Many of the products in the market use active sun-sensing techniques. Some of the products that were examined, used timer-based trackers whereas, even fewer utilized a GPS tracker. The manufactured design incorporates active power sensing. Chronological tracking has also been implemented and a comparison is made in the results section of this report. This product is intended to actively sense the sun when running in default mode, allowing the array to always receive the most efficient incident angle of light.

Moreover, a system was needed to provide the motion to the array. In earlier stages of this project it was considered to use motors to control the direction of the arrays. Upon second thoughts, not a single system used motors, as the commonality in all products was the use of linear actuators due to their ease of control and lower maintenance costs. Therefore, linear actuators were used to control the motion of the array.

To control the entire system we will be using the AVR atmega32 microcontroller due to its features when compared with similar controllers in the market, its low power consumption and mostly due to the fact that programming is easy, burning is easily done via an In System programmable option and the working knowledge of the microcontroller.

3.4 Electronics Description

The electronics for the intelligent solar tracker has been designed keeping in mind the tasks which it would be required to be performed. In designing the electronics, working of Lorentz ETA track was observed and its design requirements were also kept in mind such as:

a) High precision sensing at high speed of solar panel current & voltage (for MPP calculation)
b) Low power consumption of circuitry while calculating Max Power point of PV panel
c) Use of efficient and robust motor drive integrated IC for linear actuator
d) Charging battery with on-board solar panel and adding over-charge protection for long and durable autonomous operation
e) Reading sensor output from actuator without errors
f) Maintaining battery level to cater for cloudy days. Also the system requires power to operate and the linear actuator for moving the assembly.

For the purpose of trouble free electronics design, the approach has been to build separate modules for each task separately and finally to integrate them together when all requirements have been met. This approach allows tackling each sub-circuit individually and closely monitoring and evaluating performance. The electronics has therefore been divided into five (05) basic and fundamental circuits, each performing their own separate task. These are as follows:

a) Max Power Point circuit
b) Battery charge controller
c) Motor driver for linear actuator
d) Linear actuator sensor reading circuit
e) AVR Microcontroller generic board

3.4.1 Max Power Point Circuit (MPP)

Conventionally the method of measuring the power output of a solar panel is to connect resistors of various values to the panel and measure the voltage. The measurements can be used to calculate the power output. The same measurements can be used to plot the power output and create a performance graph for the panel. Solar panel calculations are shown in fig.8. and solar IV curve is shown in fig.9.

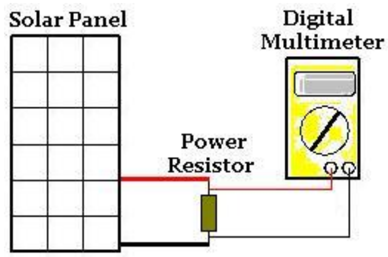


Figure 8. Solar pannel VI calculation

Results are tabluated and V I is the power.

Resistance (Ohms)	Voltage (V)	Current (A)	Power (W)
Open Circuit	30.9	0.00	0.00
100	28.8	0.29	8.30
50	27.0	0.54	14.58
25	22.5	0.90	20.25
3	3.1	1.03	3.20
Short Circuit	0	1.10	0.00

Table 1: Results of Varying Load Resistance

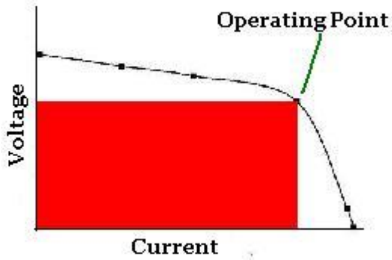


Figure 9. Solar pannel characteristics VI curve

A solar cell may operate over a wide range of voltages (V) and currents (I) as shown in Fig 2. By increasing the resistive load on an irradiated cell continuously from zero (a short circuit) to a very high value (an open circuit) one can determine the maximum-power point, the point that maximizes V×I; that is, the load for which the cell can deliver maximum electrical power at that level of irradiation as shown in Fig 2. Maximum power is typically produced with 75%- 80% of Voc and 90% of Isc. The MPP circuit provides the setup to the AVR microcontroller to measure solar panel output power in real time.

Two MPP calculation techniques have been implemented; these include PWM based power calculation and an analog switching technique.

3.4.1.1 PWM based circuit

The approach used here is to use resistor of known value and connect in to the circuit for short intervals of time by switching using PWM varying between ZERO (open circuit) to 100 % (short circuit). What this does is essentially give a virtually varying resistor with which a PWM factor can be added.

Effective Resistor value = 0.1x PWM % x Known Resistor value

For example, if the known resistance is 0.9 Ohms (wire wound), then PWM of 70 % will give 70 x 0.1 x 0.9 = 0.63 Ohms. In this manner resistance is varied and for each PWM, a set of voltage and current values is obtained which is then multiplied by the microcontroller to calculate power at that particulate load. Schematic is shown in fig.10.and PWM is shown in fig.11.

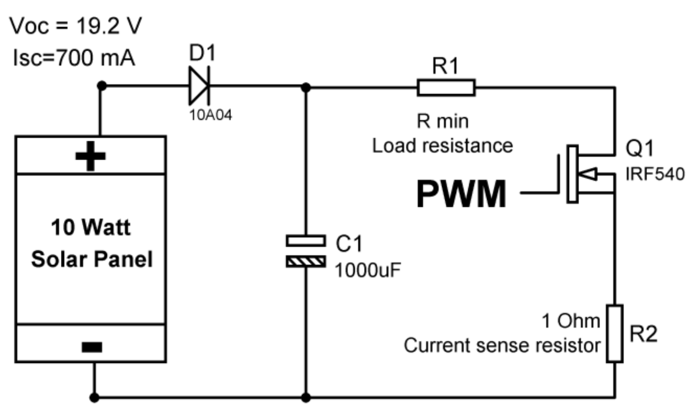


Figure 10.PWM based MPP calculation schematic

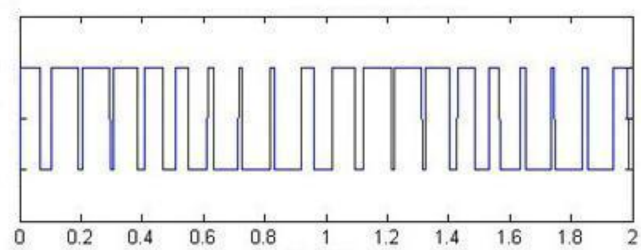


Figure 11.Varrying PWM duty cycle

PWM is varied from 10 % to about 95 %, in steps of 05 % each for coarse scan and 01 % in case of fine scan. For each PWM percentage, corresponding current and voltage values are multiplied to get Max power point at one particular orientation of the solar panel.

3.4.1.2 Problems Encountered in Design of MPP Circuit

The circuit suffered from noise in instrumentation of voltage and current readings, for the controller. A current sensing resolution of 2-5 mA was needed because slight changes in current and voltage increase the overall efficiency of the tracker to cater for very minute changes in power. So the circuit was re-designed using differential voltage sensing bringing the noise down to negligible value. Current differences in the order of 1 mA can now be detected.

Most instrumentation amplifiers are dual voltage and consume a lot of power. In the initial design the INA128 was used, but due to complex circuitry in generating negative supply rail for the INA128, we have now shifted to the INA122, it is a very low power (60uA), high precision Instrumentation amplifier that can be operated over 100 KHz, and is ideal for battery powered applications because of its single supply operation. (Please refer to attached datasheet for details)

Special consideration has now been given to the fact that while calculating MPP, the power consumption is as less as possible and the battery is kept charged at all times. Due to many design iterations keeping power consumption in mind, there has been a significant improvement in reducing battery power consumption.

Moreover, by reducing the component count of Instrumentation circuitry very low power is consumed. While the MPP is calculated, the power is drawn from the panel and NOT the battery. This gives us plenty of power for other operations.

This technique was abandoned later on in favor of the analog technique due to the following reasons:

1) High speed switch meant the voltage and current values varied with high speed and as a result chances of errors are greater.
2) The power is calculated in 5 seconds, mainly due to ADC sampling time.
3) Using the on-board 10 bit ADC of microcontroller becomes even more time consuming.

3.4.1.3 Analog switching circuit

The second MPP calculation circuit is based on using analog switches to vary the resistive load on the panel and determine different points on the VI curve and calculate the MPP. The number of points that can be determined is related to number of analog switches. A total of 2^n values are obtained from (n) switches. Switches are turned ON in binary sequence with the resistors varying from highest to lowest. The resistor values of the switches are 330, 120, 100, 82, 100and 270 Ohms respectively.

Each switch is turned ON for 7.3 ms (6ms on time and 1.3ms 10 bit ADC conversion time), and voltage and current readings are taken, the signals are conditioned via an instrumentation amplifier, which is specifically designed for battery powered data acquisition systems. Each voltage and current value gives a point of the IV curve, Fig 12 shows the operation of the circuit and in this manner the Max power point is calculated with very low power loss.

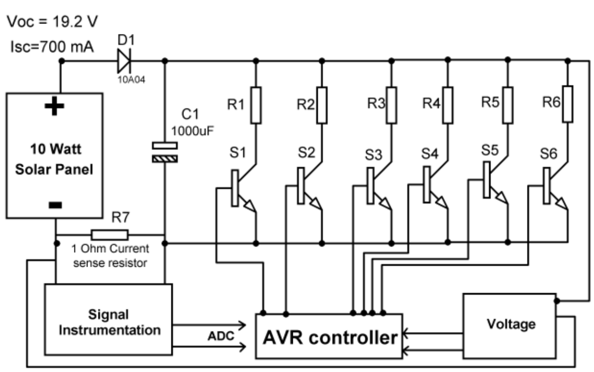


Figure 12. Schematic for analog switch circuit

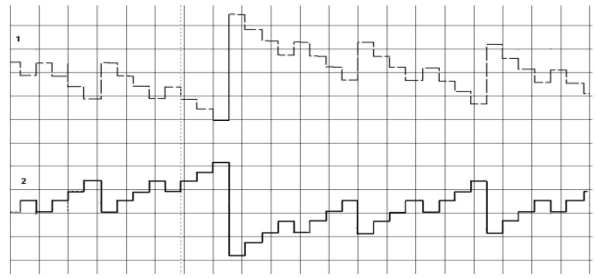


Fig 13: This is the DSO output of the analog switching MPP circuit.   The upper curve represents the drop in voltage of the solar panel as a result of the load applied to it via the resistors while the lower curve indicates the rise in current.

The current measurement circuit uses differential measurement and avoids ground loop errors. In this way a change in current as low 1 mA can be detected. The ON time of 6 ms is adequate enough for the current value to stabilize. In a similar manner, an instrumentation amplifier (INA122) is used to measure voltage of the solar panel. Both load-voltage and open circuit are measured during the same time.

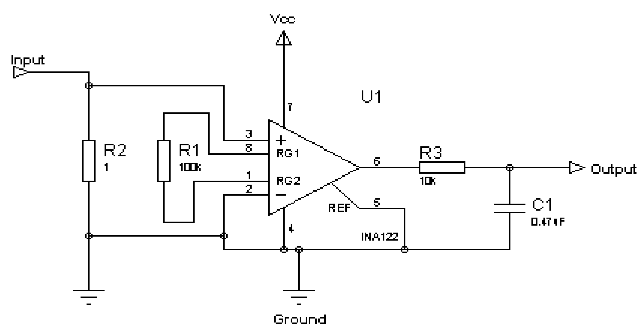


Figure 14. Current and voltage measurement and instrumentation

3.4.2 Battery Charge Controller

This circuit ensures the on-board 4.5 AH battery is charged at almost ideal conditions. The battery voltage is monitored, and if fully charged, the battery is cut-off from the panel to avoid any overcharging. As solar panel outputs 500-700mA current, it is ideal for charging the battery one tenth of its rated capacity, which is the ideal current at which a sealed lead acid type battery should be charged. The battery charging is monitored by the microcontroller differentially the same instrumentation amplifier (INA122). At 13.7 VDC, the battery is disconnected from the panel, and at 12.2 VDC, it is reconnected to re-charge again. The biggest challenge for the system is to keep the battery charged in case of cloudy weather. For this purpose, if the battery voltage drops below 12 VDC, the tracking is stopped and the tracking moves to noon position, waits for the sun to charge the battery to an adequate level and tracking resumes.

3.4.3 Motor Driver for Linear Actuator

An integrated motor driver (L298) has been used. It consists of two drive stages which have been paralleled in order to cater for high currents. The driver also provides current measurement and ability to disable the drivers and save power. A detailed datasheet is attached in Annex as reference.

3.4.4 Linear Actuator Sensor Circuit

The angle of the linear actuator is determined with a reed sensor built into the actuator by the manufacturer. The reed sensor is an electrical switch operated by a magnetic field. As the shaft of the linear actuator rotates, the electrical contacts of the reed switch are opened and closed, this results in a series of electric pulses being generated. The frequency of the pulses depends on the speed of the actuator.

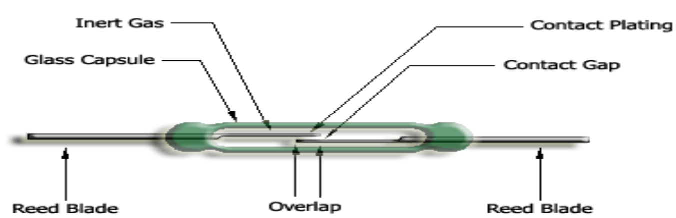


Figure 15 . A reed sensor, as the contacts come toghter, the reed blades are shorted

Figure 15 shows a description of the reed sensor operation. As the shaft rotates the reed contacts open and close.

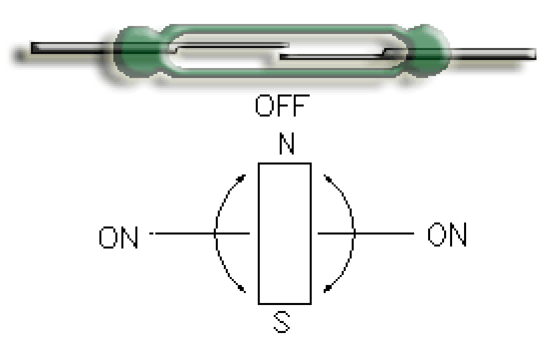


Fig 16 . A reed sensor, as the contacts come toghter, the reed blades are shorted

A very simple approach has been used for monitoring the pulses, the schematics below shows the circuit has to be energized and the pulses are fed into the on-board ADC of the microcontroller.

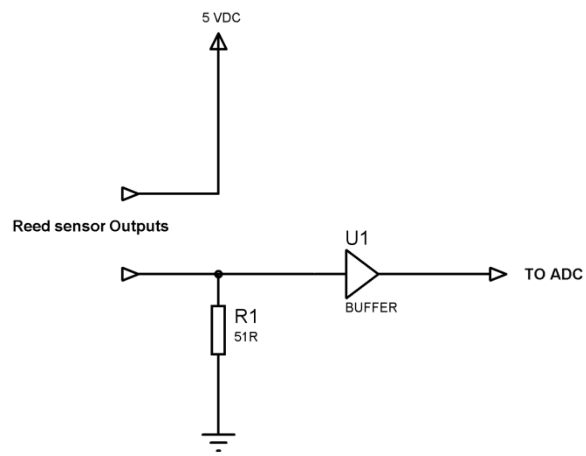


Figure17. Schematic for reed sensor

By using 8 bit ADC to monitor voltage level, read the sensor output is determined without any errors. The output is further discussed in the results section of this report.

3.4.5 AVR microcontroller

Because of the huge size of data to be retained by the controller, the entire program has been switched to AVR-ATMEGA32. It has 2Kbytes of SRAM and 32Kbytes of hex file. The SRAM consumption is at 1907 bytes against a limit of 2048 bytes. The complete algorithm has been written in this controller and simulated on proteus.

3.5 Mechanical Description

Figure18. A View of the tracking system

3.5.1 Structural Parts of Tracker

The individual parts of the tracker are given as follows:

- Mounting Pole (1 pc)	Square tube 150x150, 2750 mm length (1a)
- Beam (1 pc)	Rectangular tube150x100, 2500 mm length (1b)
- Cross Beam (1 pc)	Rectangular tube150x100, 1000 mm length (2)
- Pole connector (4 pcs)	Steel angle 63x63x6, 280 mm length (3)
- Cross Beam con. (2 pcs)	Steel angle 63x63x6, 330 mm length (3a)
- Hinge fixation (3 pcs)	Steel angle 63x63x6, 213 mm length (4)
- Hinge lower part (4 pcs)	Welded steel 200x70x120 mm (5)
- Hinge upper part (4 pcs)	Welded steel 150x50x30 mm (6)
- Centre Rail (4 pcs)	Square tube 50x50, 3400 mm length (7)
- Connecting tube (2 pcs)	Square tube 40x40, 2500 mm length (8)
- Connection clamp (7 pcs)	Steel angle 40x40x4, 70mm length (9)
- Upper motor fixation (1 pc)	Steel angle 50x50x5, 70 mm length (10)

- Lower motor fixation (1 pc) Steel angle 276x276, 63x63mm (11)
- Module fixation clamp (48 pcs) Stainless steel 50x50x1, 2mm (12)
- Standard parts (1 set) Bolts, washers, nut
- Linear motor (1 pc) (13)
- Controller fixation (2 pcs) (14)
- Reinforcement Profile (1 pc) Steel angle 50x50x5, 290mm length (16)

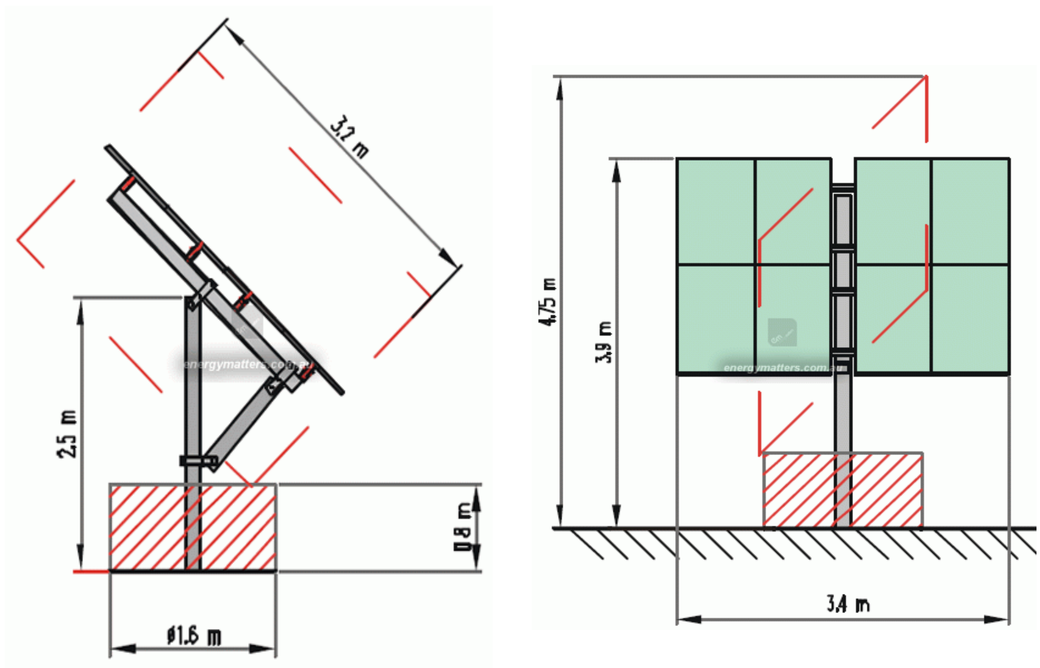


Figure 19. Basic Dimensions of the tracking system

3.5.2 Foundation

Before mounting the tracing system foundation it is necessary and that the support is made of concrete material of approx 1.6m^3. A surface foundation for the tracking system has to be constructed to assure the correct operation for the indicated maximum of module surfaces.

While setting mounting pole into foundation care must also be taken to align it exactly with the south position as illustrated in the figure below:

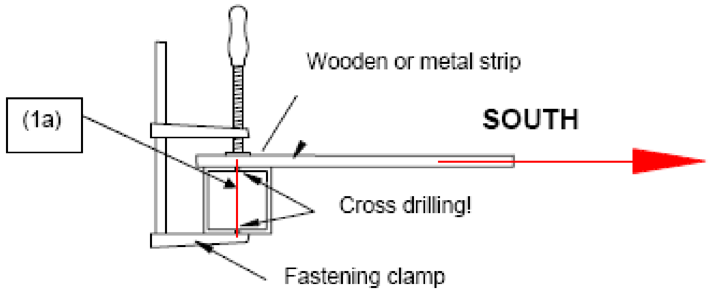


Figure 20. Arrow showing the right direction for pole and foundation placement

3.5.3 Reinforcement Profile

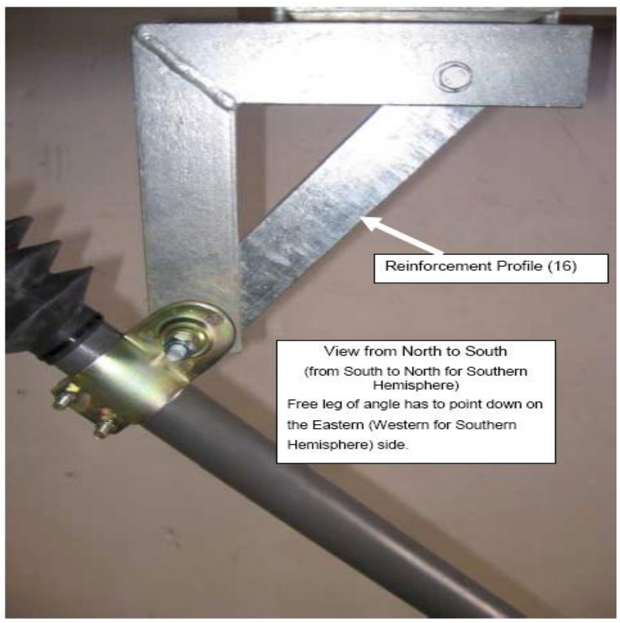


Figure 21. Arrangement of lower motor fixation

The reinforcement profile is necessary as the load in this case does not affect the actuator while in static position.

3.5.4 Assembly of Linear Motor

The distance between the two bolts on the actuator needs to be 235 mm in order for the tracking to commence properly.

Figure 22. Actuator placement

3.5.5 Additional Features

- All connection elements for parts of the tracker: steel, zinc coated, strengthening class 8.8
- Screws for standard fixation of solar modules: M6, high grade steel A2

3.6 Battery Requirements

The most important challenge for the tracking system is to maintain good battery capacity while performing its tracking operations. The tracker is required to function continuously for months at a time without any external means of charging the battery. Therefore, the state of the battery is the MOST crucial parameter, even more than tracking itself. A small (10 Watt) solar panel used for calculating power also charges the battery when the power is not being calculated. Battery power is consumed by the AVR microcontroller, the instrumentation circuits and the linear actuator. Note that, battery charging is slowed or stopped during cloudy days and these factors were also taken into consideration during the design process. In addition a (16 x 4) LCD has also been connected with the system for the purpose of monitoring system parameters and viewing previously recorded data. In view of the above mentioned facts, the need for the battery to be kept charged at all times influenced other design considerations for all the modules of the tracking system. In order to keep the battery charged the following was required;

1) The microcontroller chosen needed to be low power and not have any power consuming features that were not required for our project.
2) The linear actuator that moves the 400 kg load of the tracker assembly from east to west during the day needed to be highly efficient, requiring less current for movement.
3) The tracking strategy should have as less movement as possible. No redundant movements of the system.
4) Instrumentation should require very low power.
5) Maximum Power measurement circuit should losses should be as less as possible.
6) Maximum Power measurement calculation requires battery charging to discontinue, so it should be completed in a very small amount of time.
7) The linear actuator drive circuitry should be disabled when it is not being used to avoid any power loss.

3.7 Control Techniques Employed

3.7.1 Chronological

Chronological is the science of arranging events in their order of occurrence in time, such as use of time line. In chronological tracking the tracker always moves to perfect angles. It has nothing to do with power being accumulated. The angles are determined from the longitude and latitude of the location and the date and time. Chronological data has to be fed into the controller of each tracking system separately. It is an open loop system, and does not cater for cloud compensation or active monitor the power generated by the panels.

3.7.2 Power based

In power based tracking the tracker always actively senses the power being accumulated by the solar array. In this way this tracking strategy is in some aspects independent of the angles (azimuthal).The power based tracking systems are always concerned with maximum power accumulation. They can detect changes in the operating point where the maximum power is generated and accordingly make changes. In our design, a single 10 Watt solar panel at 12 VDC is used for Max power point calculations. Power based tracking can compensate for changes in temperature, clouds, and dust etc.

3.7.3 Comparison

In chronological tracker, power is not the deciding factor. Thus in cloudy weather the chronological tracker will continue to point towards clouds regardless of the fact that it might gain more power in a nearby angle. Moreover the chronological tracker is not general purpose but has to be programmed for every location and for every time.

Thus power based tracking is more preferred as compared to chronological tracking which has no feedback system.

Chapter 4-IMPLEMENTATION

4.1 Introduction

This chapter deals with the selection of Mechanical and Electrical control units for the tracker on the basis of techniques described in chapter 3 and comparison tables, included in the following chapter. The way of receiving the data from the tracker is also briefed in it.

4.2 Parts Selection

4.2.1 Motor driver selection

One of the objectives of this project was to produce a single PCB that incorporates all the modules of the project. Due to this, space requirements dictated that an integrated motor driver be used that is has the following features:

1) DC Motor drives capability of up to 4 Amperes, while the linear actuator typically consumes 700mA and up to 2 amperes at startup.
2) Low cost
3) Motor current measurement
4) Low power loss and ability to disable drivers to minimize power consumption.
5) Integrated package- means low component count and small footprint on the PCB layout.
6) Easily available.

4.2.2 Microcontroller selection

A comparison has been made between three familiar families of microcontrollers and results are tabulated below:

Feature	80c51	AVR	PIC
Boot strapped	NO	✓	NO
ADCs	NO	✓	✓
LOW Cost	✓	✓	NO
Low Power	NO	✓	NO
PWM pins	NO	✓	✓
Buffered outputs	NO	✓	✓

Low Development cost	✓	✓	NO
Non-volatile memory	NO	✓	✓
Real time clock	NO	✓	NO
Processor speed	NO	✓	NO
Brownout detection	NO	✓	NO
Analog comparator	NO	✓	✓
Sleep modes	NO	✓	✓
Online help	✓	✓	NO

Table 3. Comparison between different controllers

In view of the above comparison it can be easily seen that there is not much of a difference between AVR and PIC but owing to the low cost of AVR atmega series and In-system Programmable feature, the AVR was preferred over the other controllers.

4.2.3 Linear actuator selection

One common factor in the study and analysis of all commercial solar trackers was the fact that all employed linear actuators instead of motors. The reasons were quite clear. The low maintenance costs and ease of control in this particular application gave the linear actuator a clear lead over the motor .In addition to keeping track of angular position is much simpler and easier in case of a linear actuator.

Second step in the selection process was to actually choose one. A linear actuator was providing with a ball screw mechanism and reed sensor, which was incidentally perfectly suited for the task.

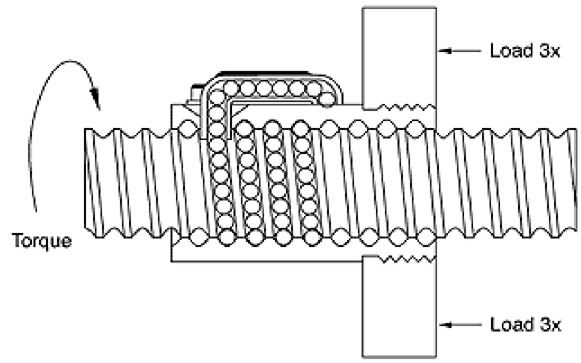


Figure 23. Ball screw mechanism in the linear actuator with lead screw

The ball screw mechanism has a clear advantage over the ACME type as the friction in the lead screw of ball screw type is much lower than ACME. This translates into less current required to move the same load. A fact also indicated by Fig. 24 shown below:

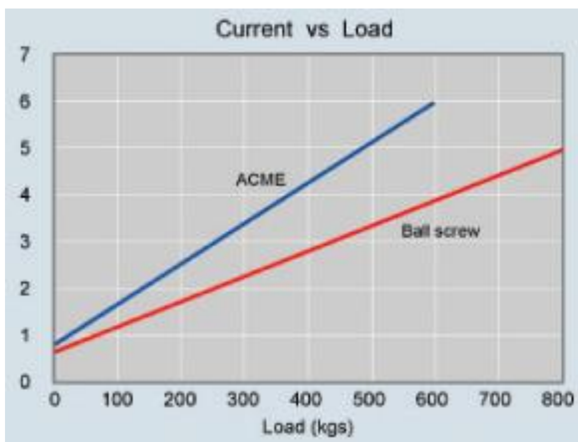


Figure 24. Current vs Load graph for linear actuator

The speed of the actuator is also more in case of ball screw type linear actuator as shown in Fig. 25. This means the tracking system can move faster and use up lesser amount of current. Thus choosing ball screw type improves performance by a considerable amount.

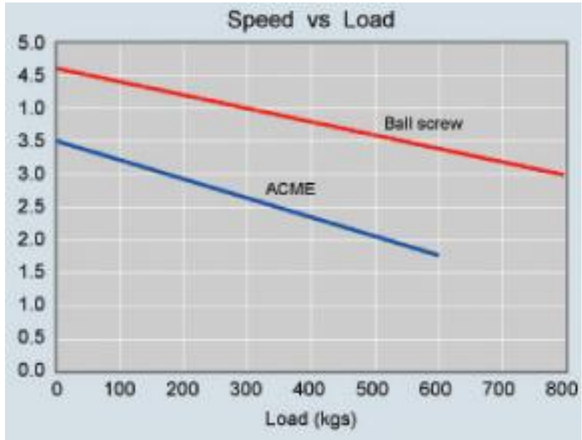


Figure 25. Speed Vs Load graph for linear actuator

4.2.4 Instrumentation amplifier selection

There are a large number of instrumentation amplifiers available in the market today. In this project these are required in order to increase / decrease the Gain, remove noise from the circuit and make sure all readings are very accurate. The INA122 from Texas instruments has all the features required in this project. It is an automatic choice because of the following features.

Features	Quality
1. Low Quiescent Current: 60ua	Micro-Power category
2. Wide power supply range	Immune to voltage swings
3. Single supply: 2.2v to 36v	Ideal for battery powered applications
4. Common-mode range to (v–)–0.1v	Improved signal quality
5. Rail-to-Rail output swing	Low signal variation
6. Low offset voltage: 250mv max	Improved signal quality
7. Low offset drift: 3mv/°c max	Good results in extreme temperatures

8. Low noise: 60nv/hz	Better signal to noise ratio
9. Low input bias current: 25na max	Lesser current drawn for measurement
10. 8-pin dip package	Small PCB foot print on PCB layout

Table 4. Features of INA122 Instrumentation amplifier

4.3 Final Circuit Description

After testing all the parameters of all the separate modules and ensuring that all sub-circuits meet all objectives and quality to implement Solar tracking, a single PCB was fabricated. It was tested under extreme conditions of voltage, current, temperature and varying signals.

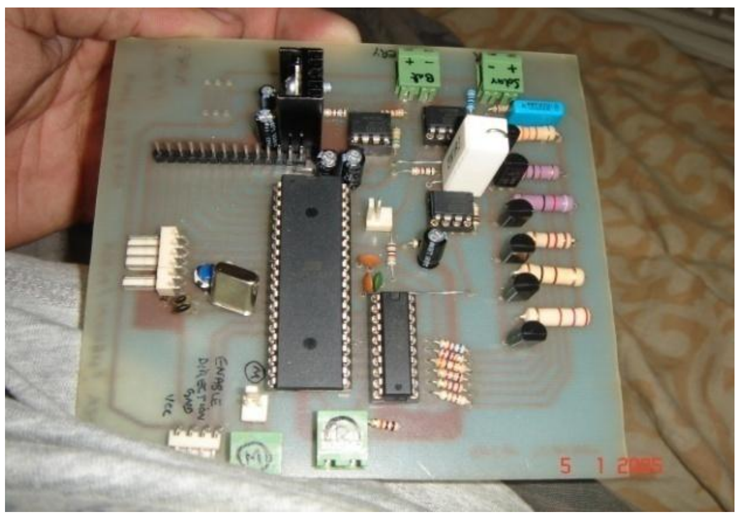


Figure 26. Picture of 1st single PCB circuit

4.4 Tracker Model

In order to speed up the development process, of testing the Hardware as well as algorithm development a model was constructed on which a single 10 Watt panel was mounted.

Figure 27. Picture of model tracker

4.5 On-site implementation

Figure 28. Tracker picture

Once, all the hardware and software was developed up to a level where it would work reliably for days and months, the on-site implementation was commenced. All results and tests carried out in the results section of this report have been carried out on the main tracking system under the supervision of the factory manager. The Tracking system, started working on June 11th, 2009. It was tested for One (01) month up till July 10th, 2009. During this time, various control strategies were implemented and their data recorded via LCD on video.

During the implementation phase the sunrise times and thresholds where the tracking would stop in the evening were duly noted. It was observed, generally that tracking commenced from 9.20 am in the morning up till 4 pm in the evening. The tracker moved 90 degrees from east position to west during this time. A static test was also conducted and results are further discussed in the results section of this report.

4.5.1 Data Acquisition

Pulse counting was done via an 8 bit on-board ADC, while the voltage and current were acquired with the help of a 10 bit ADC. This is because voltage and current are multiplied to get the power and from a tracking point of view it is extremely important to distinguish between the slightest differences in power. The resolution of power also determined the minimum step (angle) the tracking system can align with the

Data of the tests carried out was stored in the memory of the AVR microcontroller, and was displayed at regular intervals on a 16 x 4 LCD. Video evidence of the readings with gathered.

Chapter 5 – Hardware Design of Tracker

5.1 Introduction:

In order to increase the efficiency of photovoltaic panels, solar tracking systems have been developed. Regular mounted solar arrays do not optimally collect sunlight and arrays with tracking systems have been shown to increase power output by an average of 30%. Due to the expense and space required for solar arrays, this increase in power is extremely desirable.

A solar tracker is a device for orienting an array towards the sun. The sun's position in the sky varies both with the seasons and time of day as the sun moves across the sky. Solar powered equipment works best when pointed at or near the sun, so a solar tracker can increase the effectiveness of such equipment over any fixed position, at the cost of additional system complexity. There are many types of solar trackers, of varying costs, sophistication, and performance.

5.1.1 Basic Parameters of Tracker

The basic parameters of a tracker are closely associated with the mechanical structure of a particular tracker. A list of such parameters includes

- Payload (up to 450 kg)
- Mobility (single axis with 0.1 degree accuracy)
- Workspace
- Agility
- Accuracy and repeatability of positioning in various degrees of freedom
- Structural stiff-nesses, masses, damping coefficients and natural frequencies
- Economics

5.1.2 The Pro Engineer Design

Complete solar tracker was designed and simulated in the Pro Engineer environment. Here the tracker was subjected to forces which it would face in the real world and a structural study was carried out. A dynamic study was also carried out on the tracker simultaneously to find out the torques on different parts.

Finished design of tracker from different views is shown in figures. 29,30,31.

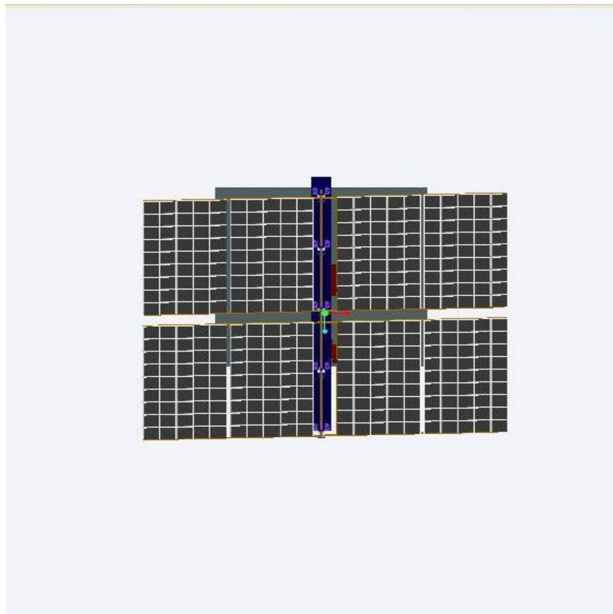


Figure 29. Top view of Pro E model

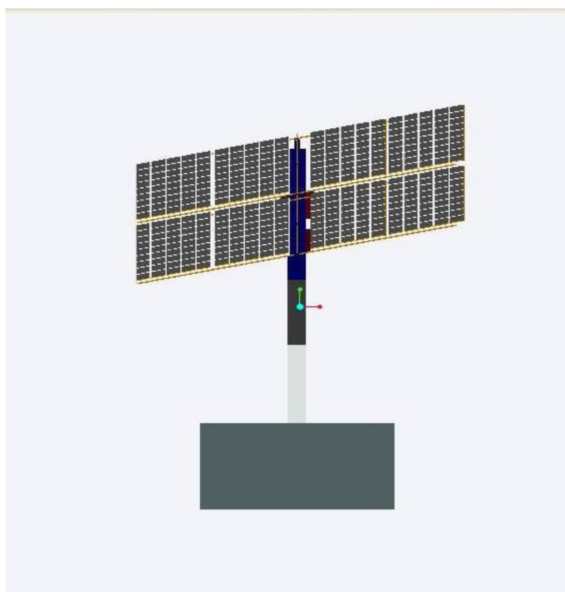


Figure 30. Front view of Pro E model

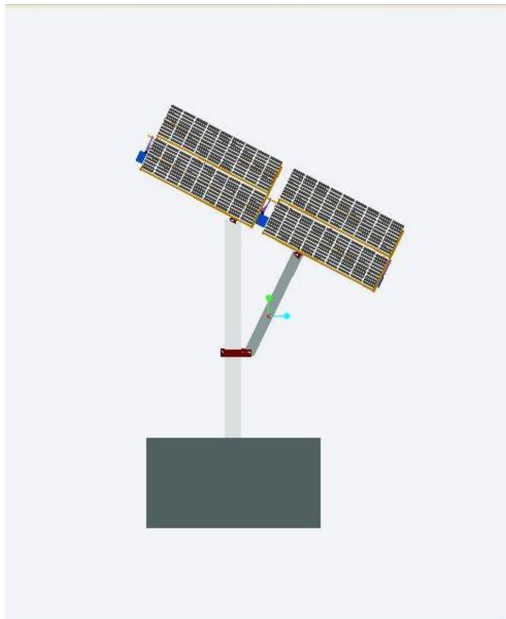


Figure 31. Left view of Pro E

5.1.3 Mechanical Analysis

Mechanical analysis of different parts of tracker was being done by applying expected force over them in Pro-Mechanica application. Following are the figures of test results of hinge and beam where maximum stress was expected.

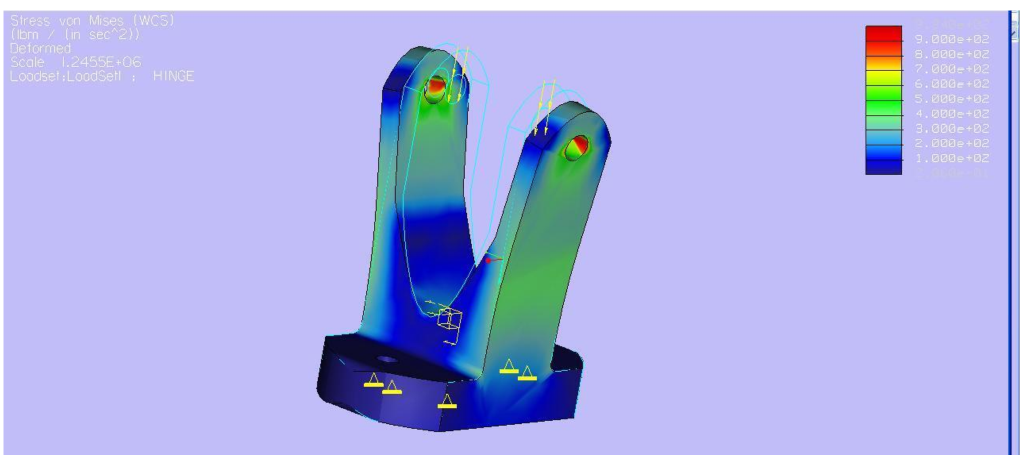


Figure 32. Hinge shear test analysis

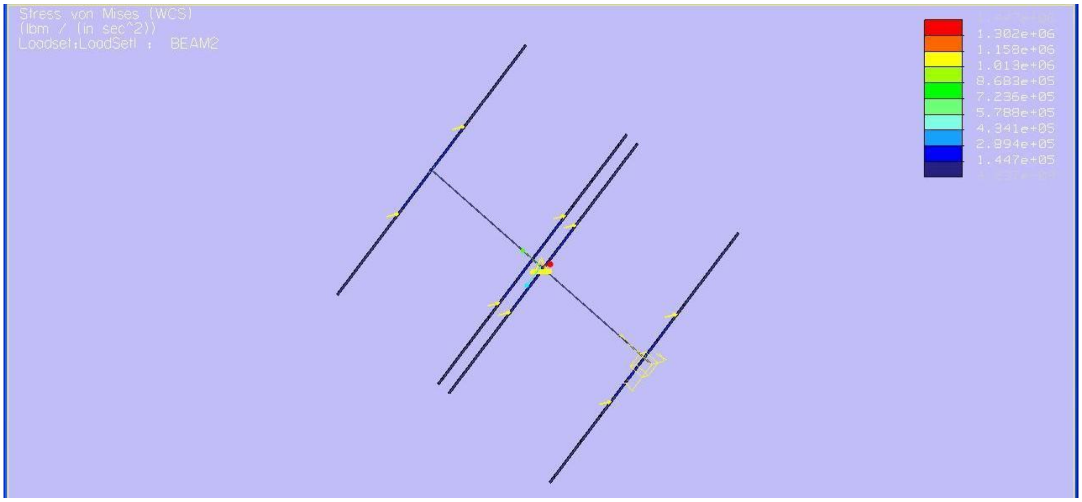


Figure 33. Beam shear test analysis

Chapter 6- Software Design

6.1 Introduction

In this chapter, the softwares used that helped in deciding critical electronics and programming decisions are MATLAB, Pro Engineer and Simulink. The Pro E model has been linked to MATLAB and important force/movement relationships have made it possible to determine the current requirements. This allows from a programming point of view to determine how much movement in one step is permissible in order to determine the best orientation which gives the maximum power.

In section 6.3 the process of algorithm development has been discussed in great detail. These control schemes and techniques have later been physically tested and results have been tabulated in the results section.

The algorithm's physical implementation has been discussed in section 6.5 with great detail and special emphasis has been given to the functions developed in the code.

6.2 Simulink

Simulink is a tool for modeling, simulating and analyzing multi domain dynamic systems [11]. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi domain simulation and design.

6.2.1 Simulink Control Design

Simulink of basic scanning technique P&O were implemented in MATLAB to simulate the power comparisons of different angles. The model is shown in the following Figure 34:

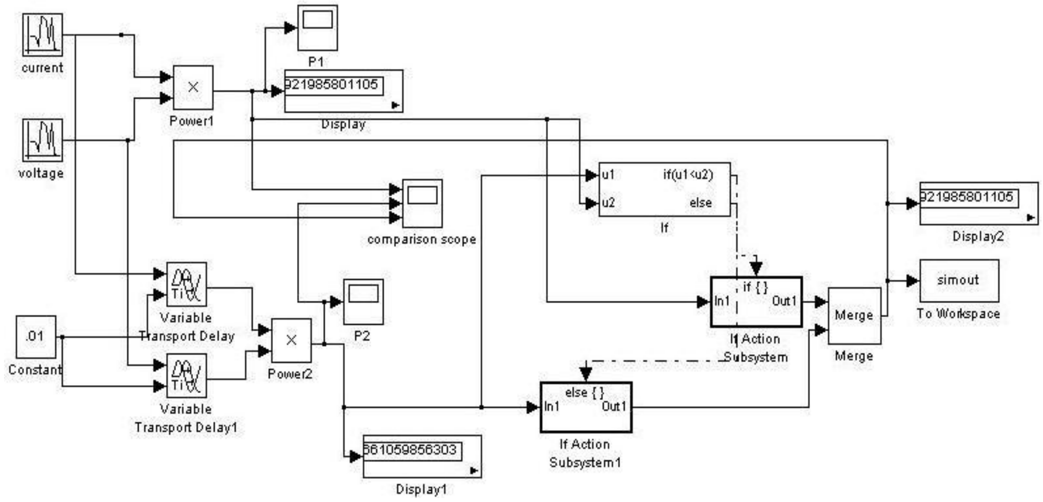


Figure 34. Simulink design of P&O

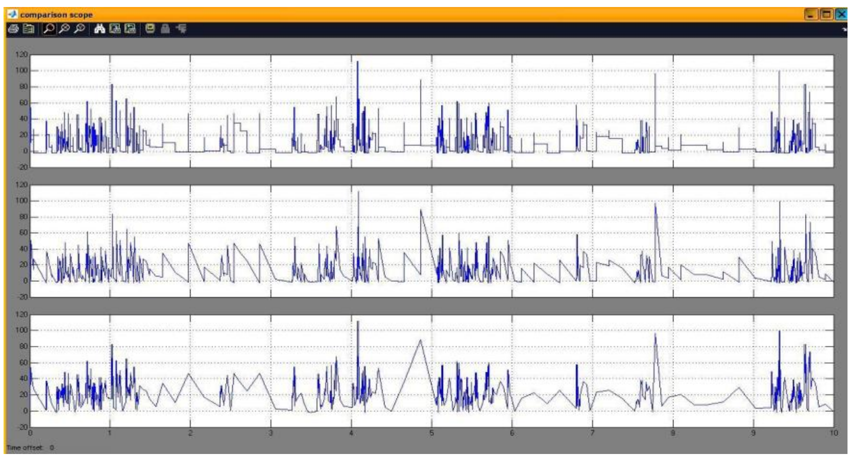


Figure 35. Comparison graph for different IV values

6.2.2 SimMechanics

SimMechanics software gives a complete set of block libraries for modeling machine parts and connecting them into a Simulink block diagram [12]. Actuator and DC motor are implemented in SimMechanics to simulate results of both in different power and force conditions.

6.2.3 SimMechanics of Actuator

Block diagram of SimMechanics of actuator is shown in fig.36 Comparison graph is shown in fig. showing that applied force is acting in only one direction.

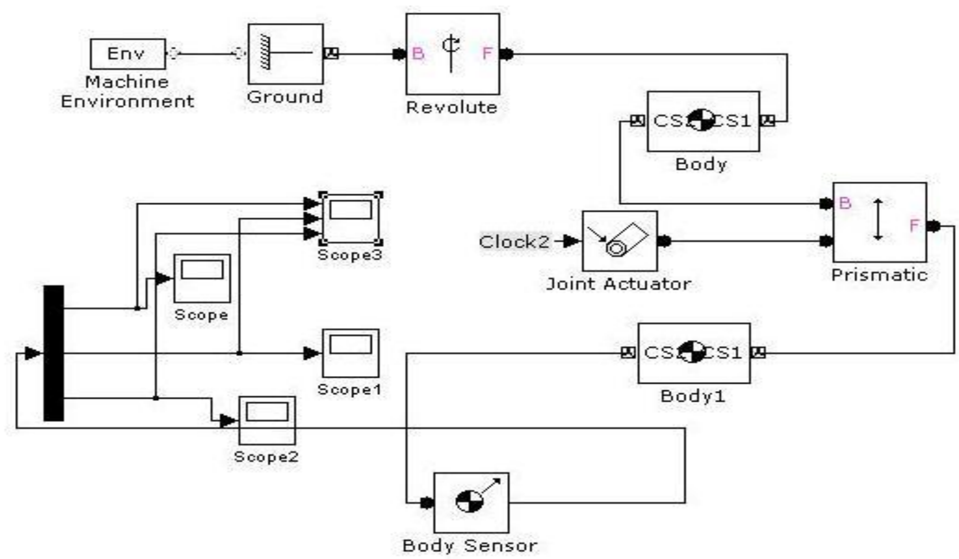


Figure 36. Actuator SimMechanics

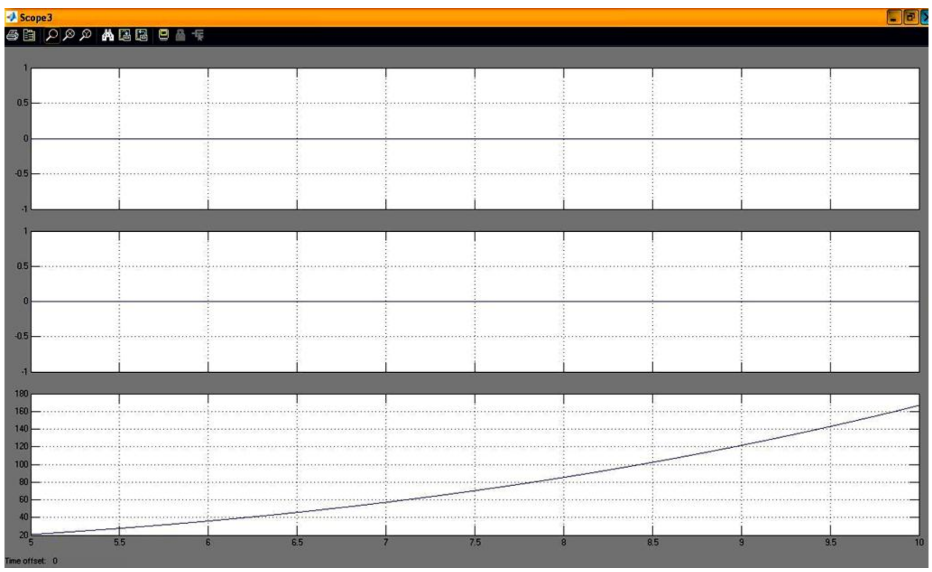


Figure 37. Effect of applied signal in X, Y, Z axis

If the change is applied a signal then actuator reaction is also changes. This behavior is shown in graph of fig. 38 and fig. 39

Figure 38. Sine wave signal reaction

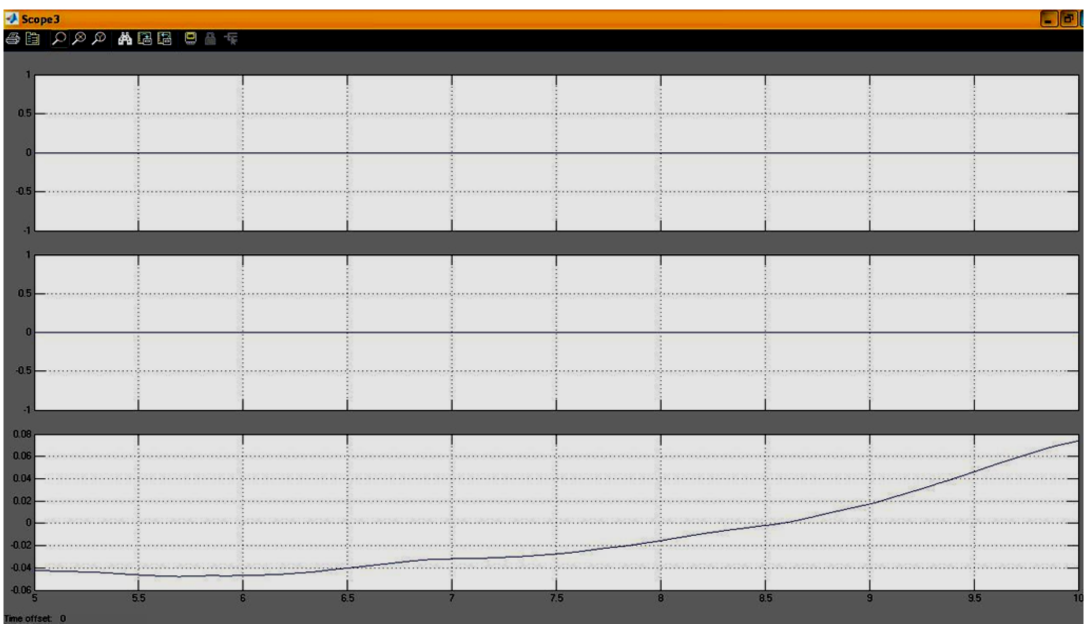


Figure 39. Random number signal reactions

6.3 Interfacing between MATLAB and Pro-Engineer

The designed mechanical model in pro-Engineer software has been imported into MATLAB with the help of "SmLink 31" software [13]. It allows the Pro-Engineer model to be exported as an .XML file. This file is then imported into MATLAB, where a Sim mechanics model can be generated. In addition, analysis can be done on the model and force-movement relationship helps us in determining the power consumption from the battery. So, in this manner this integration helps determine the amount of movement that is permissible under the given ambient conditions. SimMechanics model generated for our model in Pro-E is shown in fig.40, fig.41 and fig.42

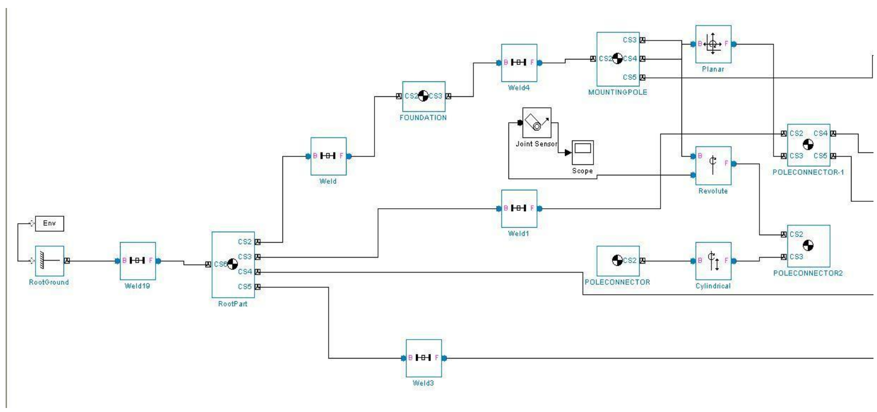


Figure. 40 Part 1 of SimMechanics

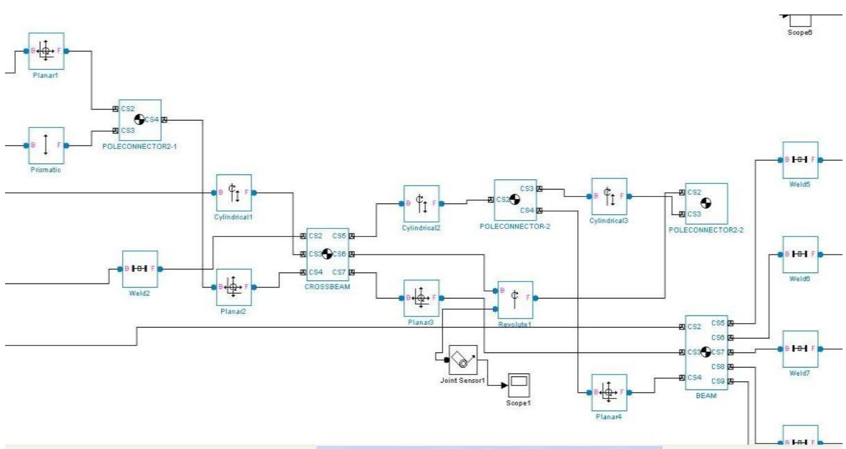


Figure.41 Part 2 of SimMechanics model

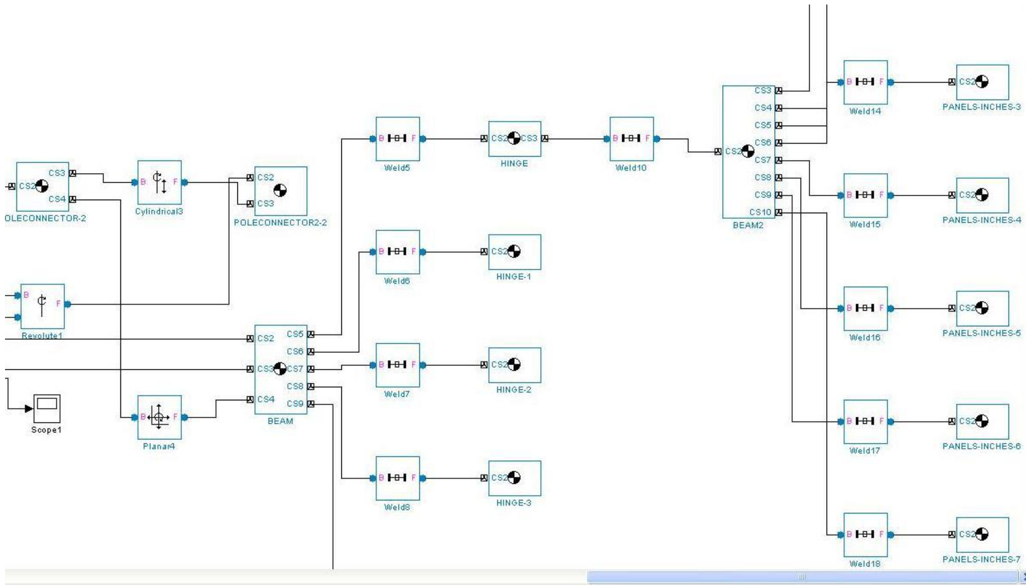


Figure.42 Part 3 of SimMechanics model

With the help of this SimMechanics model we have generated the machine model which is shown in fig43.

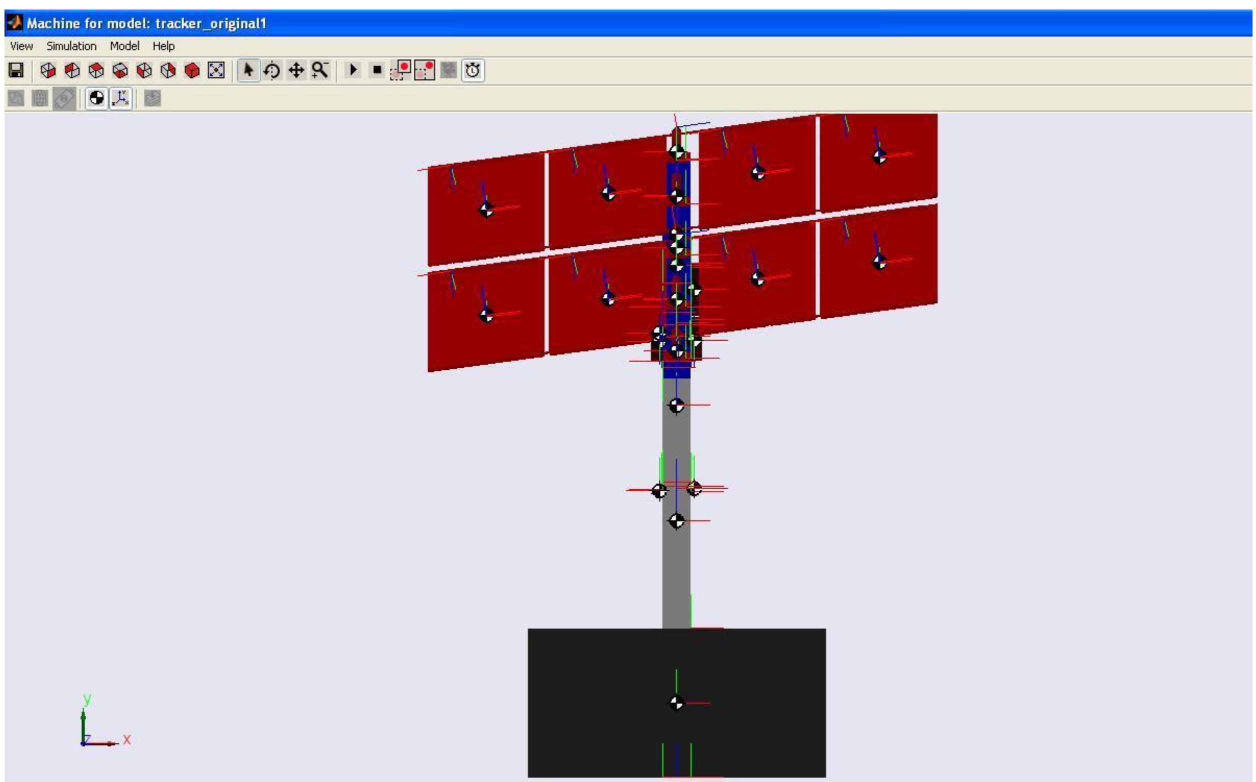


Figure.43 Machine model generated by SimMechanics

By adding scopes with SimMechanics model graph for forces of bodies and their motion-force relationship can be obtained.

6.4 Algorithm

6.4.1 Basic Scanning Technique

The algorithm is based on a very famous maximum power point tracking (MPPT) algorithm, the Perturb & Observe (P&O) algorithm [14-[16]], but has been modified to meet our power consumption requirements. The power consumption is very crucial to this tracking system since the tracking is itself solar based and has to be micromanaged so as to avoid unnecessary movements. But at the same time there can be no compromise on the tracking. Thus in order to maintain this fine balance between tracking requirements and power consumption the perturbations of the P&O algorithm had to be minimized.

6.4.2 Perturb & Observe Algorithm

The basic perturb and observe algorithm has the following fundamental steps:

1) First the power is measured at the current position.
2) Now the panel is moved in one direction (west ward in our case).
3) The power is again measured.
4) This power is compared with the power measured previously.
5) If this power is greater than the power measured initially then it will continue to move in the same direction (west) till a power drop is encountered.
6) If the power measured after first perturb is less than the power measured initially then the tracker will move back to the original position.

These are the fundamental steps in perturb and observe MPPT algorithm. They have been changed minutely in the actual code to restrict the movement of the panels. Moreover instead of returning to the position of maximum power after encountering the first downward power slope, the tracker keeps on moving till a significant drop in power is encountered. This has been done so as to avoid incorrect power point detection in cloudy or slightly windy weather.

The flowchart is basically depicting the process by which tracker will decide which position is the best for maximum power.

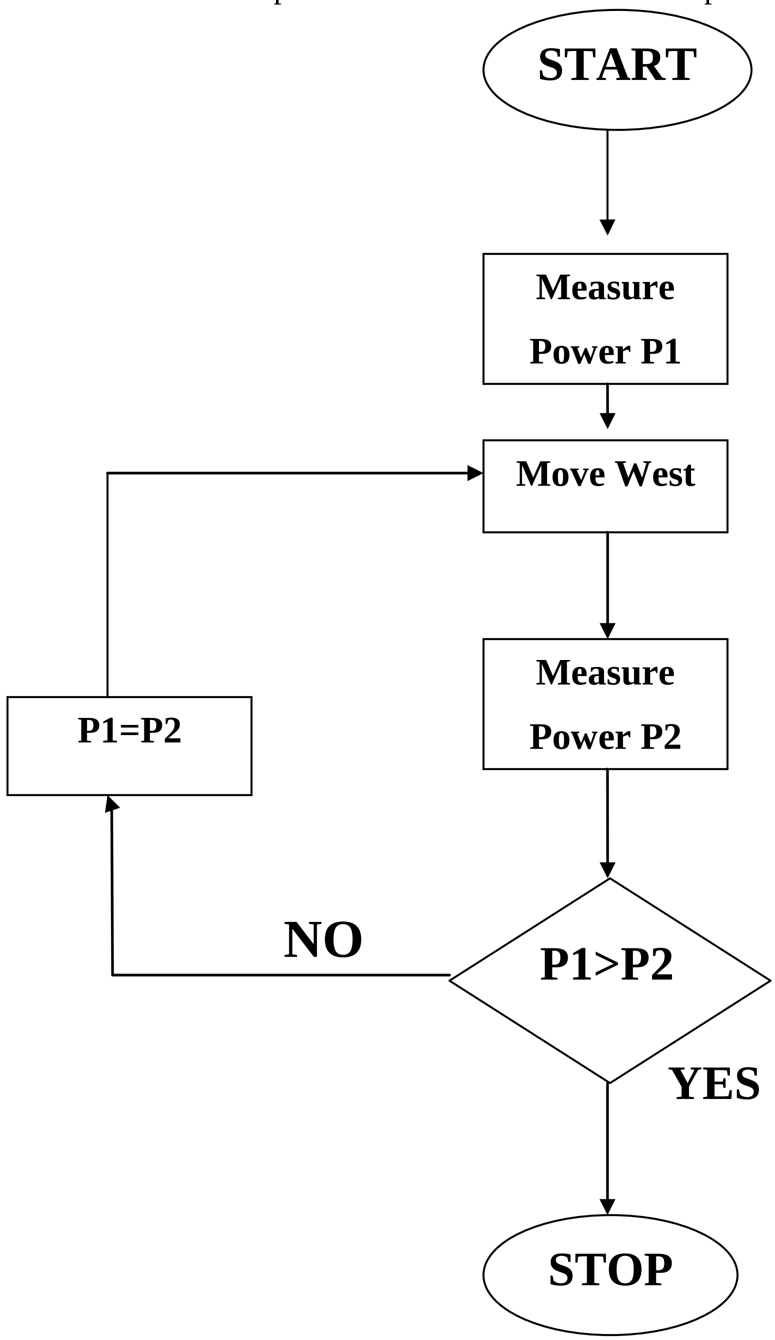


Figure 44. Flowchart of basic P & O

6.4.3 Triggering Techniques

A number of factors were considered for the tracker to move the next step. The two most important considerations are as follows:

- Power drop
- Time

On the basis of these factors two different triggering techniques were applied. They have been discussed in detail.

6.4.4 Power Based Triggering

The basic theory in power based triggering is that after a successful scanning operation has been completed, the tracker maintains its position and continues to remain in the same position till the power drops below a specified level.

This triggering technique was physically tested. The tracker was supposed to maintain the same maximum power position until the power drops more than 1.5% of the power it had gathered initially. When the power received started dropping, the P&O operation was performed and the new position and power was saved in the memory. Again the tracker would start tabulating power and would stay in this position until the power drops more than 1.5% of the new position’s power.

6.4.5 Results of Power based Triggering

There are some problems which are inherent to this technique. The problem that was faced the most was the abnormal behavior in cloudy conditions. In a cloudy weather there are rapid changes in solar power. Since our tracker was continuously monitoring power so almost after every power measurement (three minutes apart) the triggering was satisfied. In this way thus instead of avoiding unnecessary movements in cloudy weather, this triggering technique induced more movements which is a huge drawback.

Moreover, during the noon position it takes a lot of time for the power to drop more than 1.5%.So by the time, the triggering condition was achieved at noon, the maximum power point position was a lot farther than the current position. Thus, the tracker had to move a lot after the noon step had been taken.

All of this resulted in a highly random behavior which was not suitable for prediction part of the algorithm.

6.4.6 Time Based Triggering

This triggering technique is relatively easy as compared to the power based technique. In this case each step is carried out after a specified amount of time regardless of the power changes. In order to implement this technique a triggering time of 15 minutes was selected so as to strike a balance between tracking and avoiding unnecessary movements.

6.4.7 Results of Time based Triggering

The results of this triggering technique have been highly successful because it has not only successfully restricted the tracker movement by a huge degree but also provides excellent data for further prediction phase of the code.

Owing to the fact that the triggering is time based, the steps are almost taken on the same time daily, thus predicting the maximum power position on the basis of previous days' data at a specific time becomes relatively easy.

6.5 Prediction Strategy

6.5.1 Background

Scanning the sky in search of the maximum power point is relatively easy. But locating the maximum power point with minimum amount of scanning is the real hurdle. So it is desired that the tracker directly goes to the maximum power position and perform P&O for just fine adjustments. The following steps are performed in the codes that result in minimum movements owing to prediction.

1) First of all when the tracking system will be powered on the controller will bring the linear actuator to its zero position .This is necessary for a precise knowledge of the angles that will be used later on.
2) Once it is known that the angle of the panel is 0.0 degrees, we will start tracking using P&O, which as evident from its name will continue to scan the sky till it observes a downward slope of the maximum power calculated for each angle. Once the controller detects a downward slope it will move back to the angle at which maximum power was being achieved.
3) After every fifteen minutes it will scan the sky till the maximum angle of 90.0 degrees is achieved or the power being received drops below the night threshold value calculated practically.

4) This day is not saved in memory and thus the system becomes independent of any specific time for powering on the tracking system.
5) Once the condition for night has been satisfied, the tracker is brought to an angle of 45degrees or horizontal (0 degrees represent east and 90 degrees represent west position).
6) As soon as the power being received by the panel exceeds the night threshold value, the actuator moves to 0 degrees and remains in this position until the power starts to drop at the east position. This power monitoring is crucial so as to avoid unnecessary tracking of diffused sunlight. Once the power starts to drop at the east position then tracking starts.
7) The P&O is applied in true fashion with a scanning step of about 0.035 degrees .As the angle is achieved wherein maximum power being received starts decreasing by factor of 15mW; the actuator is moved back to the position where it received maximum power. This angle is saved as the first angle post morning.
8) The position is maintained for fifteen minutes.
9) After fifteen minutes step 7 and step 8 is repeated and the angles and powers are saved in memory till the power being received is less than the night threshold value.
10) As the night condition is achieved, the total power of the day is tabulated and all the data is saved.
11) It is recommended that the first complete day of scanning be a relatively sunny day.
12) Steps 6 to 10 are repeated the next day as well.
13) On the basis of the data of the first two days (relatively sunny and bright days) the third days' data is filled as the average of the first two days.
14) By this step (i.e., by 3rd night), when the panel is at the horizontal position during night, we have the data of theoretically three days derived from the data of the first two complete sunny days.
15) The first angle post morning is predicted by the following self derived relation:-
    Predicted Angle= (Average angle of last three days + Difference between last two days' angles)

16) Instead of P&0, i.e., scanning the sky till the downward slope is countered, with the help of this prediction we will reach to a very close angle to the actual angle of maximum power.

For Example:

- The first angle of first morning was 5 degrees
- The first angle of second morning was 5.12 degrees
- The first angle for the third day is the average of the first two days data
- This angle is 5.06 degrees
- On the basis of above data the predicted angle becomes
- Predicted angle=(5.06+(5.12-5.06))=5.12 degrees
- So now instead of scanning the sky after every 0.035 degrees the actuator will directly go to the desired angle

1) The actuator will again perform P&O at this angle with a scanning step of 0.035 degrees.
2) The actuator will stay at this place for fifteen minutes.
3) Before moving on to the next angle, the data for the first day will be overwritten as the average data of the first three days.
4) The data of the second day will be overwritten by the data of the third day and so on so forth
5) The data of yesterday will be overwritten by today's data.
6) Steps 19 and 20 will be completed before moving on to the next predicted angle.
7) Steps 15 to 22 will be repeated till the value of night threshold is not breached.
8) In this way the data of every day is retained as a small factor of the first day's data required for prediction.
9) Moreover, after first two days, the data keeps on modifying itself and thus the prediction becomes more accurate with the passage of time.
10) Owing to this increased accuracy of prediction, the compensation movement of P&O is decreased to a minute 0.035 degrees and thus power is conserved.

11) The algorithm improves itself with the passage of time.

6.5.2 Cloud Compensation

This is the factor which determines the efficiency of this tracker versus a chronological tracker which is based on longitude, latitude, date and time. The chronological tracker gives perfect angles but is unable to compensate for cloud cover. So far it is discussed the data related to angles, but for every step not only the angle is saved but also the power gathered at that angle is also saved.

1) Once predicted angle is reached before performing P&O, the power is measured. This power is compared with the power of previous day.
2) If the difference in expected power and calculated power is less than 1.5 watts then it means there is no cloud cover
3) In this case the P&O for minute adjustments is performed as discussed before.
4) In case of clouds the difference between the power gathered and power expected is significant.
5) When clouds have been detected, P&O is performed with a scanning step of 0.7 degrees.
6) The angle of maximum power is determined and the actuator is stopped at that position.
7) But this angle and the power of this cloudy condition is not saved as today's data rather at this step(number of movement) the predicted angle is saved as today's data and yesterday's power for this step is saved as the power of this step for today.
8) The actuator waits at this location for fifteen minutes before going to step 3.
9) In this way the data for a cloudy day is never retained in the controller memory.

DAY	Angle(Degrees)	Power(Watts)
0	20.00	4.6W
1	20.20	4.5W
2	20.30	4.6W
Today(Predicted Data)	20.35	4.5667W(Expected)
Today(At Predicted Angle)	20.35	2.2W(Cloudy)
Today(After P&O for cloudy weather)	26.00	4.2W
Today (Data that will be retained in the memory)	20.35	4.5667W

Table 5. Cloud cover data for step ”n”

6.5.3 Seasonal Changes

Since, the algorithm is supposed to be independent of the date and time, the change in day time in different seasons is a very critical aspect of the algorithm. But the change in duration of tracking is catered for intelligently by the inherent ability of this algorithm to adapt itself with different circumstances.

The case of algorithm adapting itself with change in sunrise time and sunset time can be understood with the help of following example

MONTH	DATE	ANGLE
March	23rd	41
March	24th	40.9
March	25th	40.9
March	26th	40.8
March	27th	40.9
March	28th	40.8
March	29th	40.8
March	30th	40.7
March	31st	40.7
April	1st	40.8
April	2nd	40.7
April	3rd	40.7
April	4th	40.6

April	5th	40.6
April	6th	40.5

Table 6. Case Study: Step Number 21

In the above data as the daytime is increasing (daytime increases while moving towards 22nd June and decreases from 22nd June to 22nd December!), for the same step we have to move to a smaller angle. Thus with the passage of time we will move less for the same step between December and June. In this way, a time will come that 90 degrees step will not be reached by the same step (n) of yesterday rather another step (n+1) will be allowed to take place. Simply we can say that fifteen minutes more daytime will be detected.

Example

Let's suppose that the step 38 was the last step on June 1.This step was giving an angle of 89 degrees. By June 16th step 38 is representing 87 degrees and still we have sunlight more than the night threshold. Now another step will be added i.e., 39th, at an angle of 89.2 degrees. Thus 15 more minutes of tracking will be increased.

Similarly in case of days between 22nd June and 22nd December, instead of increasing this tracking time, it will slowly start to decrease. Consider the following data

MONTH	**DATE**	**ANGLE**
August	23rd	80.0
August	24th	80.1
August	25th	80.1
August	26th	80.2
August	27th	80.1
August	28th	80.2
August	29th	80.3
August	30th	80.2
August	31st	80.3
September	1st	80.4

September	2nd	80.4
September	3rd	80.3
September	4th	80.4
September	5th	80.4
September	6th	80.5

Table 7. Case Study: Step Number 36

As evident from above data, as 22nd December approaches the angle for each step starts increasing. Consequently there will be certain step(x) that will not be taken owing to either the threshold value or the fact that 90 degrees would have been reached by a step prior to the step(x) resulting in less sunlight tracking time.

6.6 Algorithm’s Physical Implementation

In order to physically implement the algorithm it was necessary that high levels of precision be observed in dealing with the various inputs being received by the AVR ATmega32 microcontroller. A brief description of the various functions of the microcontroller’s code is given below.

6.6.1 Actuator Control

The actuator has been controlled with precision. The reed switch has been successfully decoded with the following output pulse characteristics

- The frequency of pulse waveform is 2.5 Hz at 12 volts.
- The up time is 70% resulting in 280 milliseconds of uptime.
- The downtime is 120 milliseconds.
- The total number of pulses is 1303 in this case.
- These 1303 pulses represent 90 degrees.
- So every pulse basically represents 0.069 degrees. This is the resolution with which the tracker can track the sun.

Pulse counting has been achieved by making a function which instead of taking digital values monitors the analog values of the reed switch and once a value less than 0.25 volts is observed, the function considers this value as a low pulse and then waits for 70 ms before again checking the voltage. Thus almost at the time when a high voltage is about to be received, the controller starts to again monitor the reed output via its analog channels. When the voltage crosses 4.75 volts it considers it as high level.

Thus on the basis of the above mentioned reed sensor monitoring technique the actuator function has been made which moves the panel the required number of pulses in the required direction (east/west). While moving towards west the function monitors the rising edges of pulses and while going towards east the function monitors the falling edges.

Actuator1 function is another actuator related function which makes the panel to travel to the required pulse.

6.6.2 Analog Channels

All the analog channels have been successfully tested. They have been used for:

- Actuator pulse counting
- Panel voltage measurement
- Panel current measurement
- Actuator current consumption
- Battery voltage

Two functions have been made for the purpose of analog to digital channels. One function i.e., the analog function is an 8-bit analog to digital conversion function. 8-bit accuracy has been used for reed sensor output, actuator current and battery voltage.

Another function of analog channels is analog1 function which is a 10 bit function and is used for panel power measurements.

6.6.3 Power Function

The power function calculates the power P=V*I from 64 varying loads. The 10 bit accuracy allows us to have $1024*1024=2^{20}$ different powers. The loads are varied by switching 6 loads in various digital combinations. The maximum power out of these 64 steps is returned as maximum power for that particular position.

6.6.4 Scan

This function is P&O in essence. It goes to the required angle and then moves in west direction till a downward slope of power is encountered. If the downward slope is on the very first perturb (movement), then it goes in the east direction till the same limiting condition of decrease in power. Moreover in order to restrict too much movements of the tracker, a limit of 7 degrees westward and 4.2 degrees eastward has been imposed. Thus the tracker will at the most move 7 degrees in one step.

In order to negate wind effects and haze, the tracker continues to move despite encountering downward power slope until the power drops more than 15mW in 0.035 degrees.

6.6.5 Baseline

This function is used for the algorithm implementation till the third night after switching on the tracker. The purpose of this code is to acquire the data of the first two days. The data for third day is made by averaging the data of first two days. Once we have the baseline data, the next day’s expected angles are generated and the control is transferred to the infinity function.

6.6.6 Infinity

This function is used for algorithm implementation forever. In this part of the program the predictions are made, clouds are compensated, data is updated and the code continues to refine its predictions with the passage of time.

Chapter 7-Results, Discussions and Conclusions

7.1 Introduction

This chapter deals with the results and conclusions made on the different type of analysis, and comparisons between results of different days are discussed and then conclusions are defined on the basis of difference between the results achieved.

7.2 Voltage calibration test

Using a 10 bit ADC on-board the microcontroller, voltages of different magnitudes in the target range were tested at different signal variations. The final results were very encouraging. A difference of up to 5 mV can be detected in the design. This factor holds great importance in terms of the accuracy of power calculations.

7.3 Current calibration test

For current calibration, changes up to 2 mA have been detected. Since the Max power point circuit calculates power from a 10 watt panel, it has an I_{sc} of 0-700 mA. As a result, an accuracy of 2 mA is very desirable.

7.4 Pulse counting test

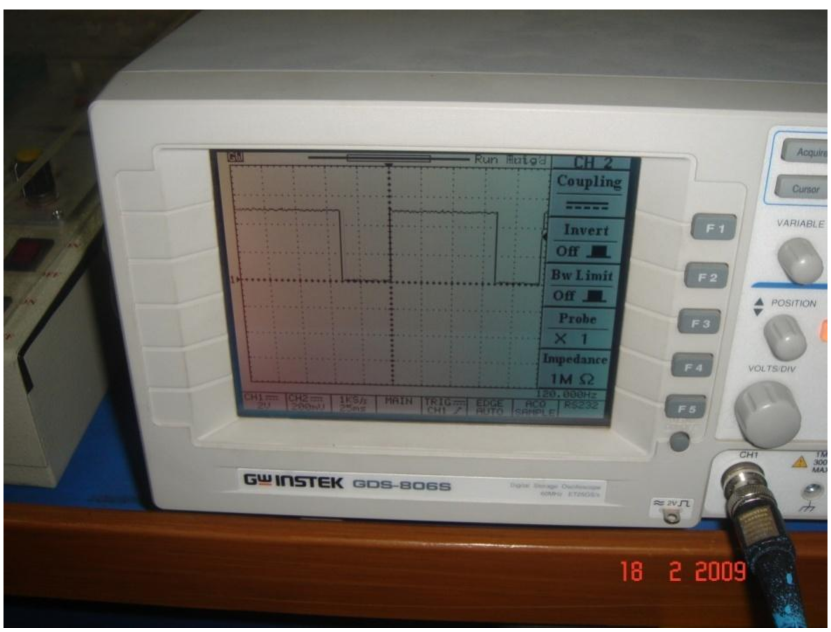


Figure 45. Reed sensor DSO output

Counting the pulses, while the actuator expands or contracts gives information about the angle at which the panels will be oriented. The pulse count while expanding or contracting is 1305.

Considering the 90 degree range, in which the panels can be moved, accuracy of 90 / 1305 = 0.068 degrees per pulse is achieved. This resolution is acceptable as an accuracy of 0.1 degree is considered to be very good. ADC voltage level monitoring ensured that a pulse was never missed.

7.5 Power benchmark test

In order to find out the min angle that would show change in power at a particular time, the following test was conducted.

Power Testing was after every .035 Degrees at various times

At 10:30 am

Isc Curve:

The short circuit current curve is showing significant changes as we travel from 0 degrees to 32 degrees thus indicating that current is a major factor in power curve.

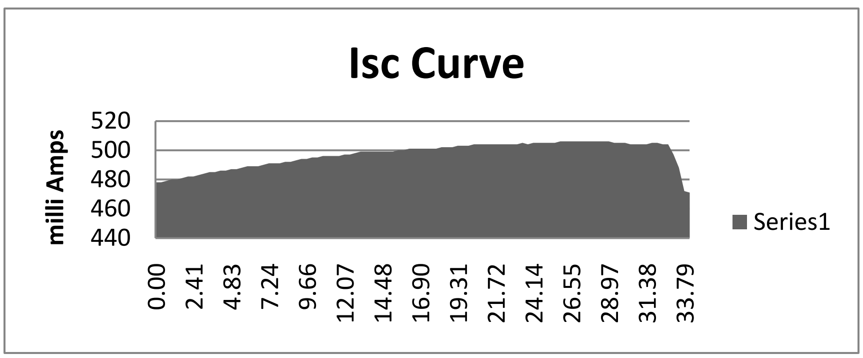


Figure 46. Isc Curve at 10:30 am

Voc Curve

The open circuit voltage curve is indicating that the open circuit voltage undergoes only minor changes while travelling east to west.

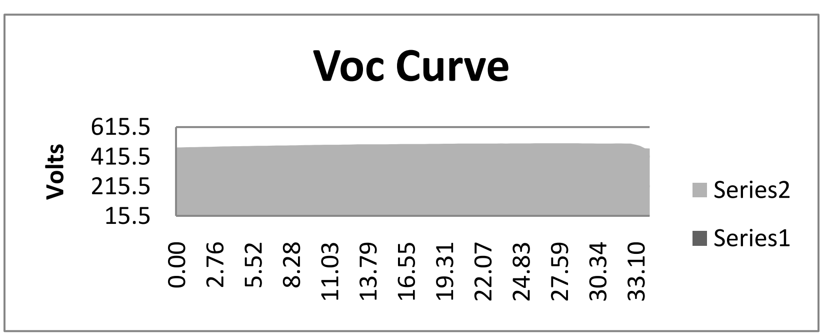


Figure 47.Voc Curve at 10:30 am

Power Curve

The power curve is a curve between the maximum power (product of V and I) of 64 varying loads. It can be seen that it is almost identical to current curve.

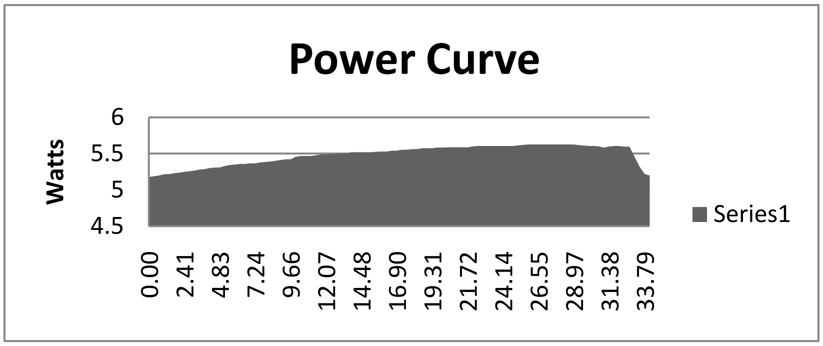


Figure 48.Power Curve at 10:30 am

Result

The maximum power point from this test is 27.59 degrees. It is this angle that the tracking system detects after performing a simple perturb and observe algorithm. Moreover it shows that V I characteristics of a panel change with the slightest change in angle.

At 10:50 am

Isc Curve:

The short circuit current curve is showing significant changes as we travel from 13.79 degrees to 47 degrees thus indicating that current is a major factor in power curve.

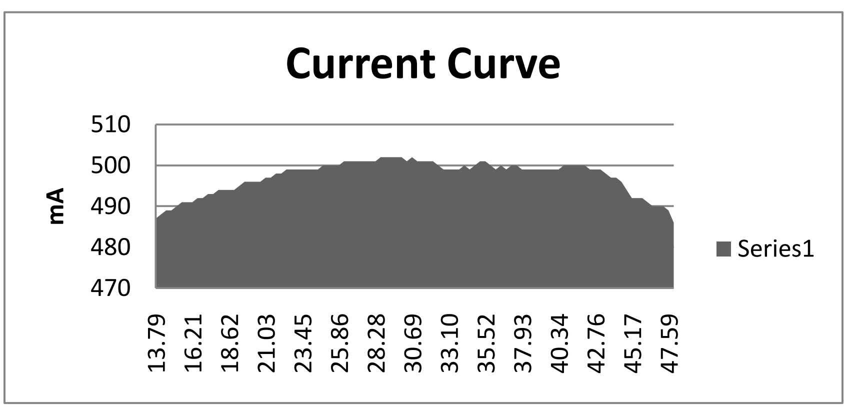


Figure 49. Isc Curve at 10:50 am

Voc Curve

The open circuit voltage curve is indicating that the open circuit voltage undergoes only minor changes while travelling east to west.

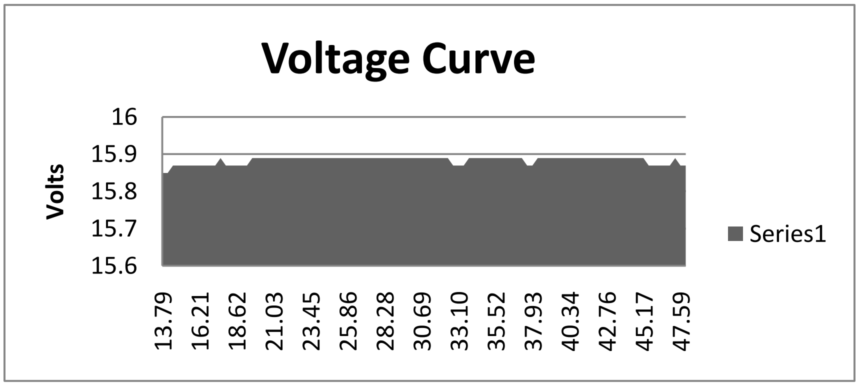


Figure 50. Voc Curve at 10:50 am

Power Curve

The power curve is a curve between the maximum power (product of V and I) of 64 varying loads. It can be seen that it is almost identical to current curve.

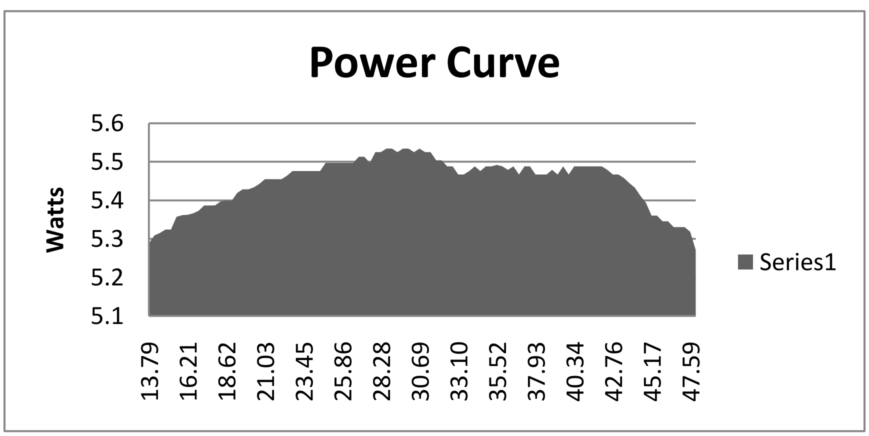


Figure 51. Power Curve at 10:50 am

Result

The maximum power point from this test is 31.0 degrees. It is this angle that the tracking system detects after performing a simple perturb and observe algorithm. Moreover it shows that V I characteristics of a panel change with the slightest change in angle. This result also shows that the maximum power point has slightly moved westward as compared to the last test.

At 8:10 am

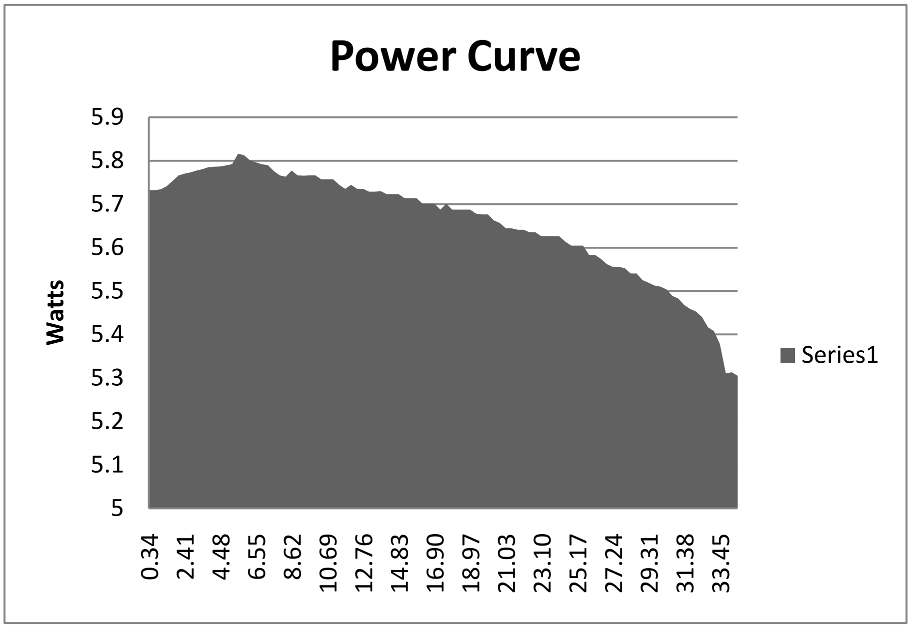


Figure 52. Power Curve at 8:10 am

This graph shows that in the morning the maximum power is received at 5.3 degrees and the power continues to drop continuously.

7.6 Power variance due to Wind

(Power Measurement at 34.5 degrees at 11:40 am)

The power measured continuously at 34.5 degrees is shown below.

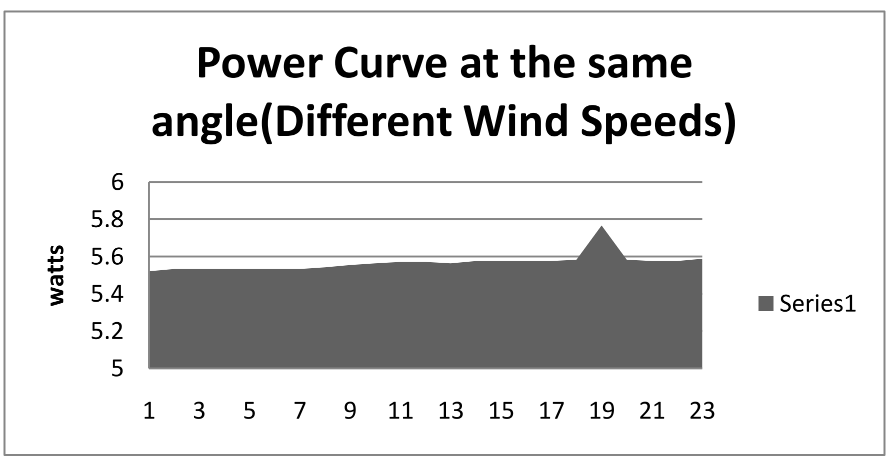


Figure 53. Power Curve for stationary panel

Similarly the voltage curve is shown below.

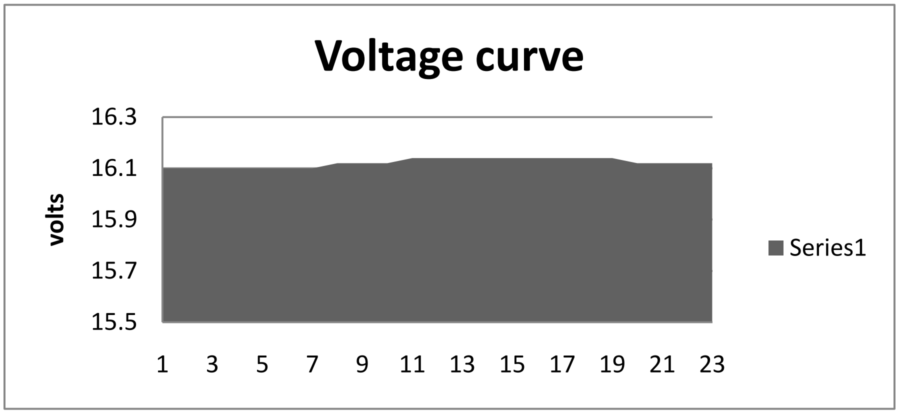


Figure 54.Voltage Curve for stationary panel

It can be seen that the power almost remains constant. It changes slightly with the change in wind speed.

Wind Effects

The effect of wind on the power gathered at the same point at the same time is shown above. As the wind speed increases

- Dust decreases from the surfaces
- Temperature of the panel decreases

This results in increase in current capability of the panel thus directly affecting the power curve at step 19 and 20.

7.7 Power based Triggering

This is the data of 8th July from 10am till 3:27pm. On 8th of July, the triggering was based on the condition that power at that particular angle had to drop more than 1.5% of the original power gathered. The following data depicts the panel angles, power, voltage and current throughout the day.

Panel Position

The following graph shows the position of the panel.

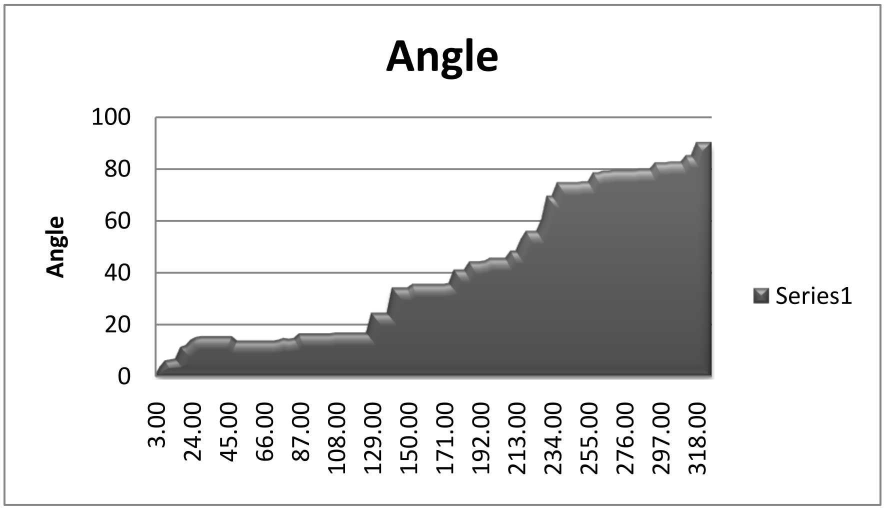


Figure 55.Panel movement for power based tracking

As it is evident that instead of smoothly travel, the tracker's behavior is a bit knee jerk type. The graph shows relatively steep slopes. The presence of steep slopes depict that the tracker was lagging behind the maximum power point for many steps thus it had to move several times rapidly to catch up with the sun.

For example, this data implies that during tracking, the power triggered tracker was unable to find any suitable angle between 56 degrees and 70 degrees. This means that while the tracker was waiting at 56 degrees for the power to drop 1.5%,the maximum power point had moved to somewhere close to 70 degrees. Thus valuable power was wasted while waiting for the power to drop 1.5%.

Current (Isc) Curve

This curve shows the short circuit current that was observed throughout the day. The current from 10 am to 3:27 pm drops gradually and steadily thus implying that power based triggering was able to maintain good levels of current for a greater part of the day.

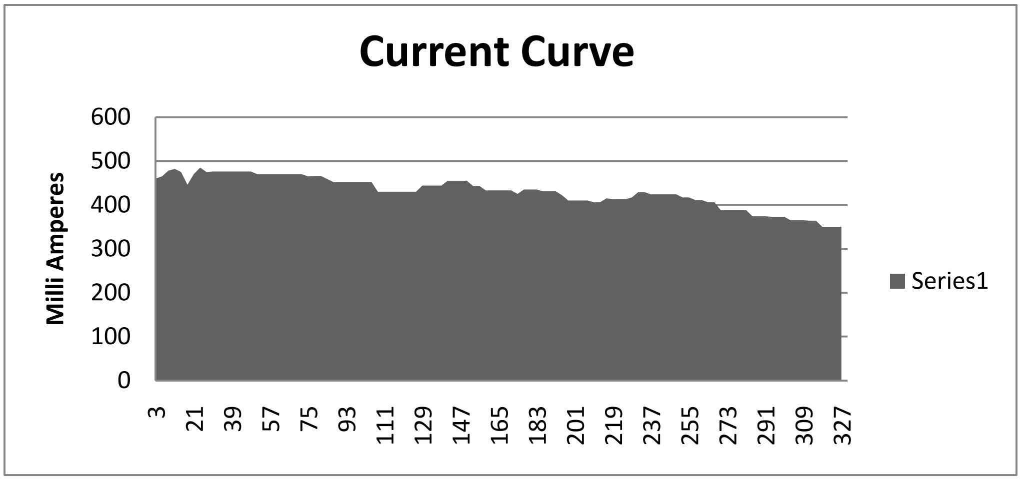


Figure 56.Isc Curve for power based tracking

Voltage Curve

Following is the voltage curve throughout the day for the steps taken throughout the day.

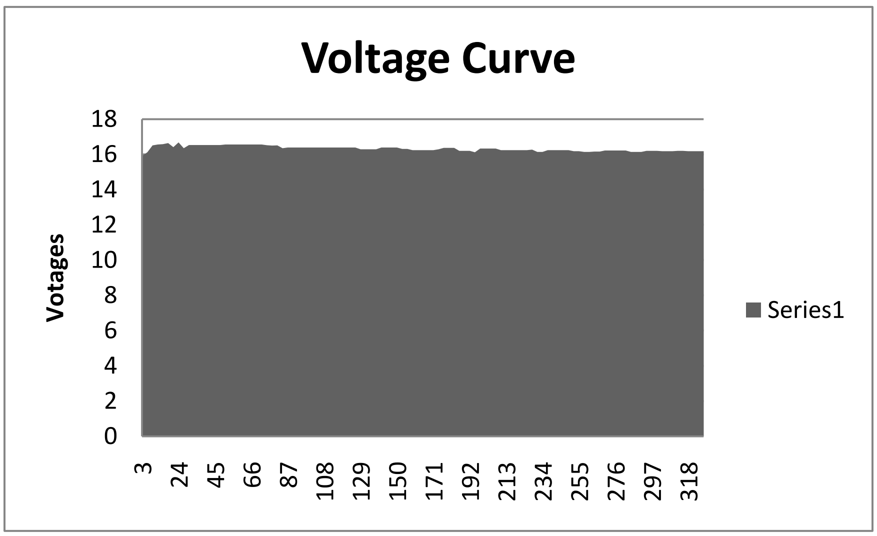


Figure 57.Voltage Curve for power based tracking

This curve like all previous open circuit voltage curve shows that power remain almost constant.

Power Curve

This curve shows the power obtained in the 327 minutes after 10am. The power remains close to 5 watts till 12:30pm and then gradually starts decreasing to 4 watts.

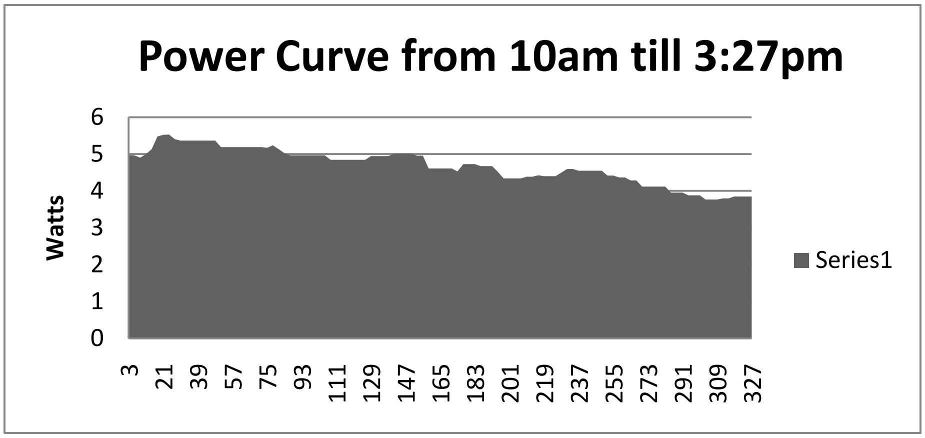


Figure 58.Power Curve for power based tracking

Conclusion

The power based triggering successfully tracks the sun but the following problems were observed in the triggering on the basis of power

- In cloudy conditions as the power fluctuations are rapid; the triggering becomes much more rapid and thus more power consumption in cloudy weather.
- The number of steps taken by the tracker in two consecutive days cannot be the same since clouds cannot be clouds.
- Moreover it is not necessary that the same number of steps take place at the same time thus prediction algorithm becomes almost impossible to be implemented with power based triggering.
- The number of steps are much more than time based triggering so it means that more memory will be consumed thus it is almost impossible to predict the position of the sun.

7.8 Prediction on the basis of triggered tracking

The prediction has been carried out by implementing P&O based scanning and time based tracking. In the following data day 0 represents 26th June, day 1 represents 27th June and day 2 represents 28th June. The predicted data is the data expected on the 29th of June.

26th June's Movements after every 15 minutes

The following data represents the movements after every 15 minutes starting from 7:00 am to 5:30 am.

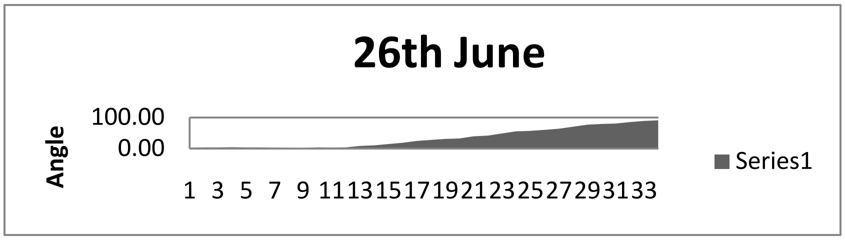


Figure 59.Panel movement on 26th June

The data shows that the movement of the tracker is much smoother than the angle curve of power based triggering.

27th & 28th June's Movements after every 15 minutes

The following two graphs indicate the almost similar movement pattern of the next two days. This movement of the pattern is very encouraging for prediction technique already discussed in the software design chapter.

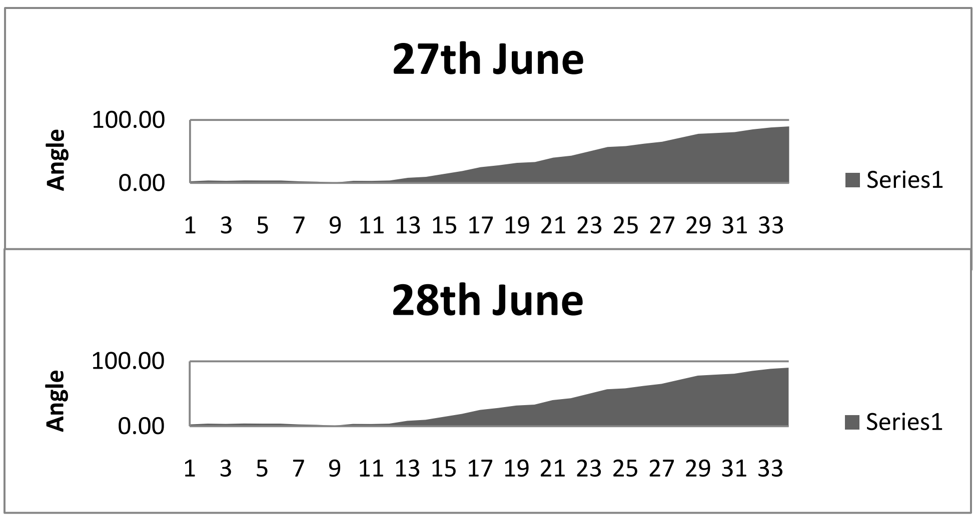


Figure 60.Panel movement on 27th and 28th June

Predicted Day's Data i.e., 29th June

The prediction is carried out by taking the average of the last three days.

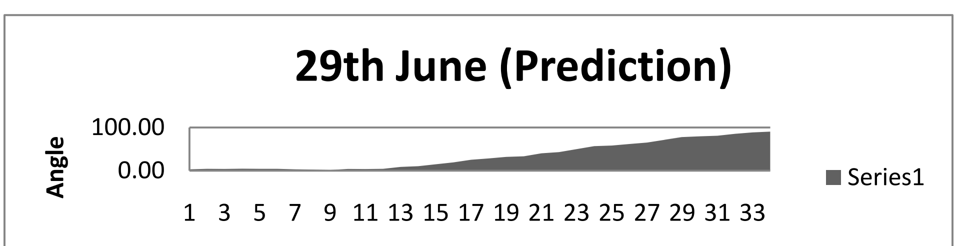


Figure 61.Panel movement on 29th June

The data is significant in the sense that it means that all the triggering is aligned to the sun rise time and it is this reason that the data is almost identical in the first three days.

Comparison between 26th, 27th and 28th June

26th Vs 27th June

This graph shows that since 26th June (Day 0) was a bit cloudy in the morning so we encountered a bit of variations between the data for 26th as compared to the data of 27th June.

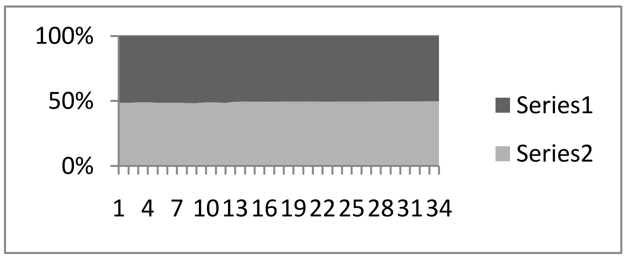


Figure 62.Comparison of 26th June and 27th June

27th Vs 28th June

In contrast to the initial data of previous days the data of this graph shows that almost the tracker was standing at the same position throughout the two days. Thus owing to the algorithm the initial wayward graph of previous days' morning has been adjusted with a greater accuracy.

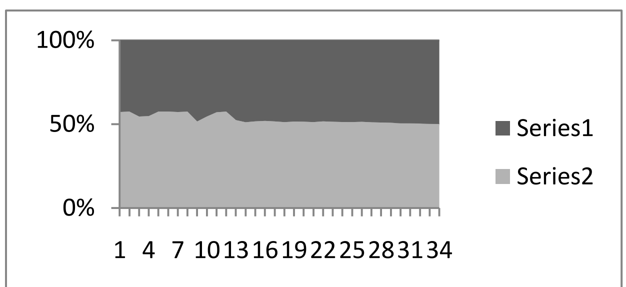


Figure 63.Comparison of 28th June and 27th June

Difference in the data of 27th and 28th

It can be seen clearly that the difference in actual data of 27th and 28th is almost negligible i.e., less that 0.5 degrees. Thus, this graph proves that more the tracker operates the better the prediction will become and better will be the battery efficiency.

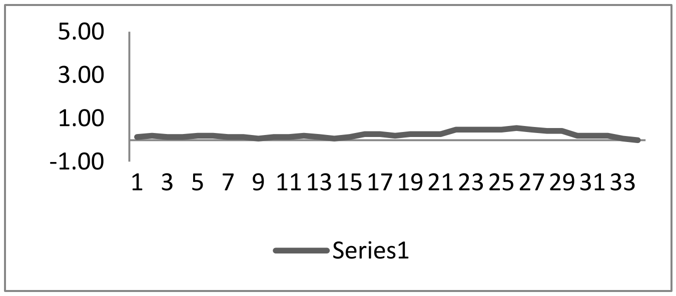


Figure 64.Error in angles between 27th June and 28th June

Difference in Predicted & Actual Days' Data

The following graph shows the variation between the predicted data for 29th June Vs the data of previous days.

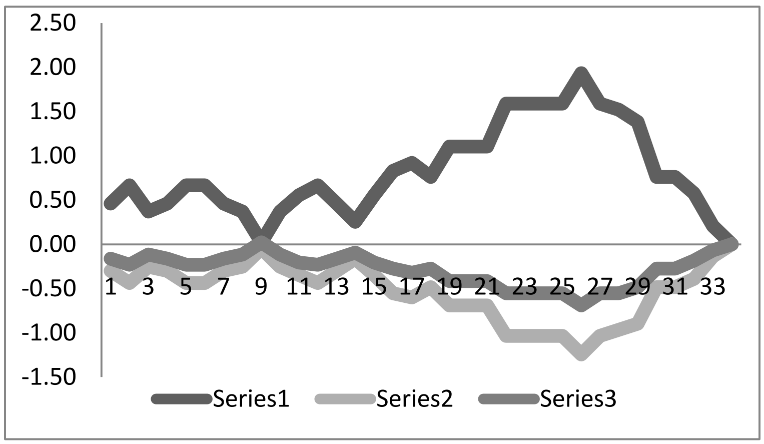


Figure 65.Error in Predicted and previous angles

The above data depicts the deviation of all the previous days' data from the predicted data (mean position). Series 1 represents 26th June and so on so forth. It is evident that with the passage of days the deviation starts to decrease tremendously. The vertical axis represents the azimuthal angle. The maximum deviation was of 1.93 degrees on 26th June which was reduced to 1.2 degrees the next day. And on 28th of June the deviation is only 0.6 degrees. Thus the prediction has improved almost three times in just three days.

This shows that the tracker is learning and improving with the passage of time. The more the tracker operates, the lesser will be the deviation; the better will be the prediction thus resulting in less tracker movements and better battery consumption.

Conclusion

The above data tells us the following things

- The tracker perfectly aligns itself with the sunrise time
- The time based triggering results in almost similar angles

- The prediction can simply be performed by averaging the angles of sunny days
- The cloudy data is quickly compensated with the arrival of sunny days
- It involves relatively less steps as compared to power based triggering thus saving precious memory
- It can easily adjust in seasonal changes owing to its alignment with the sun rise time

7.9 Comparison of tracking strategies in cloudy conditions

Test

The test was carried out on 10th July, 2009. It was a cloudy day with only a few sunny patches. The panels' movements were observed as well as the power gathered from 6:36 am till 5:24pm.

Panels Movements

Following graphs show the tracker movement throughout the day for open loop (chronological) tracking and feedback (power monitoring and time based triggering) technique.

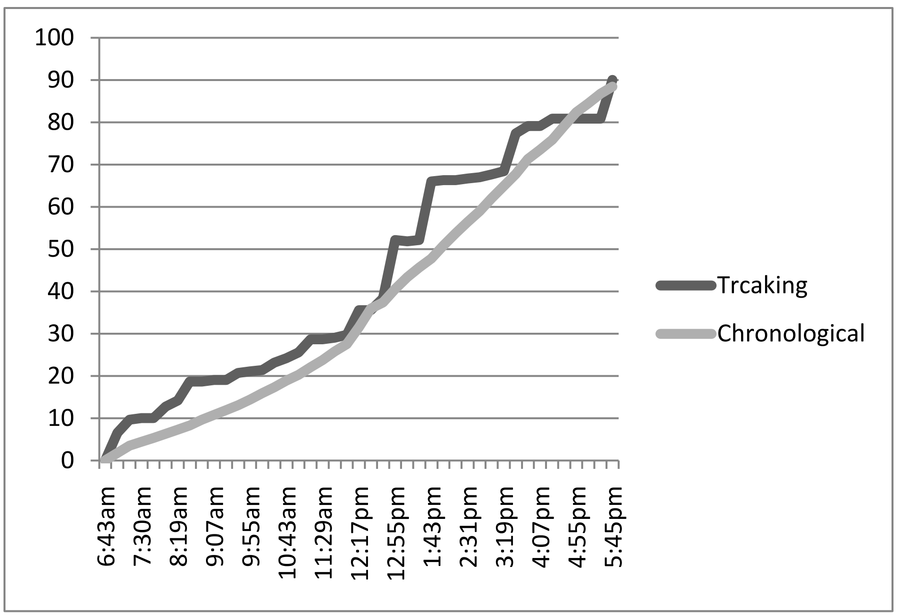


Figure 66.Movement comparison between tracking and chronological

It is evident from this graph that the chronological moves smoothly throughout the day regardless of the cloudy conditions whereas the time based tracking makes the tracker move rapidly as soon as a sunny patch is found and is always trying to gather more power.

It can also be seen from the data of 26th June that the tracker used to move towards the east till the initial two hours and then used to have a constant west ward slope. The problem of the slope being east ward has been removed in this data and the tracker moves with a west ward slope.

Power Comparison

The following graph shows the power curve in cloudy conditions for three different panel orientations.

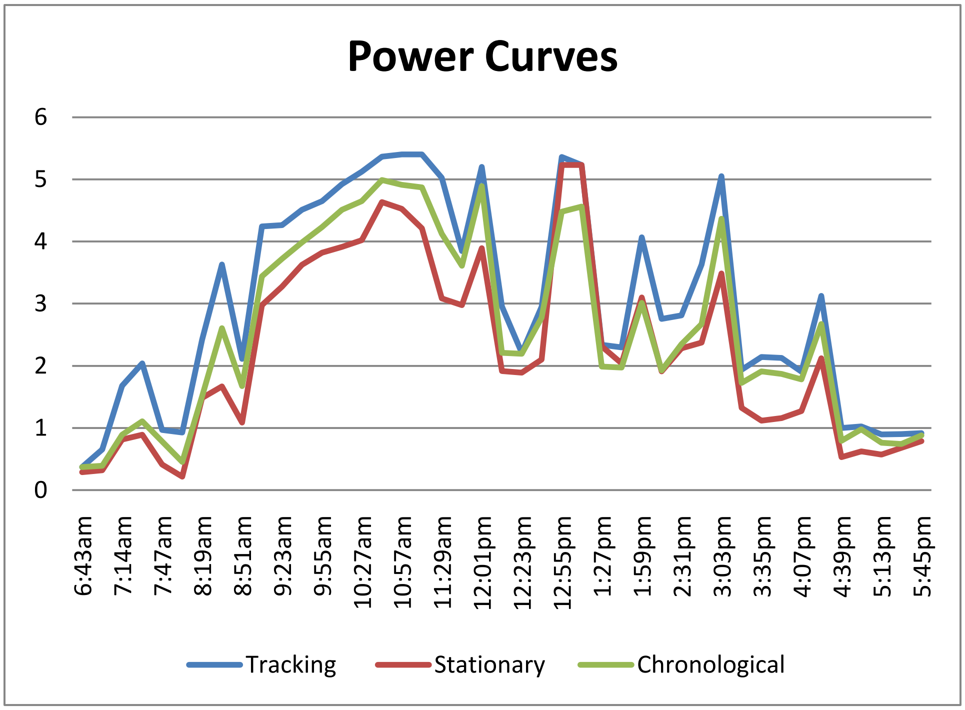


Figure 67. Power accumulated by various panel orientations

Results

Firstly it must be made clear that the zigzag nature of this curve is because of the atmospheric conditions which have resulted in huge drop of power in certain parts of the day.

- The stationary curve shows that at horizontal position there is a always a visible difference between power gathered by tracking and chronological as compared to stationary panels thus the advantage of tracking is evident from the graph above.
- The only time the stationary and tracking gathered the same output was around noon since the tracker owing to its closed loop tracking was also at the horizontal position.
- The case of chronological tracking is quite interesting in the sense that it has always gathered less power than closed loop tracking and more power than stationary tracking.
- The movements in case of chronological tracking are relatively smooth

- In case of time based tracking the movement of panels is restricted in cloudy weather and only slight adjustments are made. This fact is evident from the near horizontal slopes of the tracker movement graph.
- Moreover it can also be observed that the tracker sometimes moves rapidly (indicated by steep slopes) thus implying the tracker's ability to catch up with the sun as soon as a sunny patch comes.
- The effects of clouds are visible on all the methods of panel orientation but it is stationary panels that are affected the most followed by chronological strategy.
- The power based tracking is the minimum affected by the bad weather and moves the least during cloudy weather.
- The chronological tracker continues to move despite the cloudy weather thus wasting battery power.

So, the chronological tracker gathers less power and moves more than a power based tracker which captures more power and that too by moving less. Thus closed loop tracker is better than an open loop tracker.

7.10 Power loss analysis

Measuring Max power from the panels is a very important factor. The MPPT calculation circuit takes 64 readings at different points along the VI characteristic curve of the solar panel. Each calculation takes 7 milliseconds. Thus MPP calculation takes 448 ms to complete, this means that the battery charging has to be disconnected for Half a second each time the tracking system. This result is very desirable since it took 7 seconds to calculate power via the PWM method. Another observation made in the previous section is that movement from the predict time based triggering tracking strategy is less as compared to other tracking methods. As a result less time and power is spending if this technique is applied.

7.11 Conclusions

The following facts can be safely concluded in lights of the various tests performed on the tracker from 11^{th} of June 2009 to 10^{th} of July 2009.

1. Tracking gathers 30-40% more power as compared to stationary panels.
2. Tracking is most beneficial in morning and evening time.
3. The power characteristics (loaded) of photo voltaic panels are similar to the short circuit current Isc characteristics of the panel.

4. The open circuit voltage undergoes minute changes throughout the day even in cloudy conditions. Voc remains mostly constant.
5. The maximum power point of a photovoltaic panel is instantly affected by changes in temperature, wind speeds and dust particles.
6. Tracker movement is enhanced in power based triggering thus limiting its effectiveness
7. Moreover power based triggering sometimes lags the maximum power point position (during noon especially) and then has to move too much in one step.
8. The chronological tracker gives perfect azimuthal and altitude angles but our concern is power not perfect angles. Maximum power is not achieved at perfect angles because of unpredictable and varying atmospheric conditions.
9. Chronological tracker continues to move despite cloudy conditions thus battery drains out quickly in unsuitable battery charging atmosphere.
10. The time based triggered tracking restricts movements in cloudy weather and at the same time gathers more power than stationary and chronological trackers.

Chapter 8- Future Recommendations

1. Owing to spatial and economic constraints the solar technology is moving towards concentrated photo voltaic (CPV) cells. The concentrated photo voltaic cells have Fresnel lenses which concentrate the solar rays on the solar cells thus enhancing the solar cell output. This creates a much higher electricity output than photovoltaic material. For the installation to work it is essential that the CPV panels follow the sun during the day. It is imperative that CPV should have a dual axis tracking system so that rays are always concentrated on the exact location of the solar cells.CPV require an accuracy of 0.1 degrees. The tracking system discussed above provides this accuracy but is a single axis tracker. More research needs to be carried out on achieving this accuracy on dual axis trackers.
2. More research can be done on Concentrated Solar Power (CSP) which is based on concentrating sunlight onto a small surface which is then heated. The heat is converted to energy through either a sterling engine or a fluid that is heated and used for power generation. Precise movement is essential for this installation to work effectively.CSP can be obtained through different solar power systems such as a solar tower with heliostats, whereas heliostat is a device that includes a mirror, usually a plane mirror, which turns so as to keep reflecting sunlight toward a predetermined target.

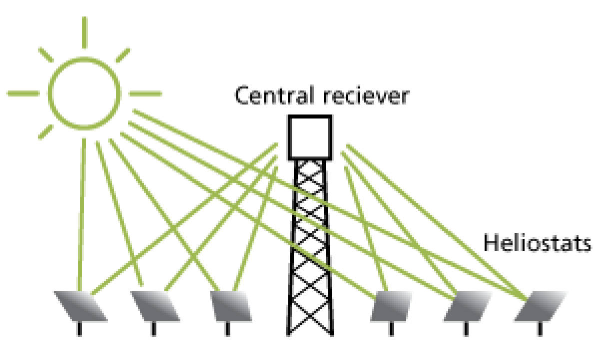


Figure 68. Concentrated Solar Power

3. Similarly dual axis tracking must also be implemented on photo voltaic cells so as to increase the output of PV panels. Dual axis trackers have two degrees of freedom that act

as axes of rotation. These axes are typically normal to one another. The axis that is fixed with respect to the ground can be considered a primary axis. The axis that is referenced to the primary axis can be considered a secondary axis.

There are several common implementations of dual axis trackers. They are classified by the orientation of their primary axes with respect to the ground. Two common implementations are Tip-Tilt Dual Axis Trackers (TTDAT) and Azimuth-Altitude Dual Axis Trackers (AADAT).

Figure 69. Dual axis Tracker

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