Maximum Power Point Tracking Under Partial Shading Conditions Using an Embedded System

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1   Contents

Table of Figures

Table of Tables

Abstract

The effects of global warming are deteriorating the planet and have enforced strict legislations for carbon footprint reductions. One of the main causes of global warming is the use of fossil fuels for power generation. Renewable energy is the solution to this problem as it produces electricity in a clean way. One of the promising forms of renewable energy is photovoltaic. However, solar is intermittent source of energy and dependent upon a number of factors including solar intensity and shadowing effects. This work aims to develop an effective and inexpensive microcontroller based control scheme to track the maximum power point in standalone solar photovoltaic power systems.

In conventional photovoltaic systems, the power curve has a single peak of power. There are many algorithms to track maximum power to maximise the efficiency of the photovoltaic system. However, when the photovoltaic is partially shaded, the output power can have multiple power peaks. A unique algorithm is derived to find the largest peak out of the many peaks. The entire power curve is scanned to find the maximum peak with respect to voltage, using a microcontroller. The largest peak is known as the global peak then presented to the output.

The most commonly used algorithms; "perturb and observe" and "incremental conductance" were used. The scanning process is then repeated after a certain amount of time to maintain the global peak. The algorithm has achieved this with minimal loss of power. The algorithm scans and finds the global peak in 15 minutes of intervals, this process takes one second. Therefore, one second duration of power loss occurs from the photovoltaic in every 15 minutes.

The algorithms are embedded in parallax microcontroller. Compare to the numerical Simulink model of photovoltaic systems experimental tracking efficiencies are slower. Nevertheless, in principle of the algorithms, perturb and observe works better than incremental conductance technique in terms of accuracy. The concentrated photovoltaic is required to move 11 times on an average day by using 0.7 W of power each time it moves, that of which the current photovoltaic modules can provide.

Acknowledgments

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1   Introduction and background

1.1 Different power resources

Day by day technology is becoming more advance and common. Every house hold around the world is advancing to make their lives easier by adapting to technology. The power of electricity produced around the entire world is not sufficient enough to provide the public. Furthermore the world population increases by 1.2 % per year that is approximately 1.5 billion people every year[1]. Providing fresh water, electricity and other essential living services will inevitably become a challenge as the population increases. On average a household in the UK will use 4170KWh[2]. Potential tasks carried out by people are being replaced by electrical counterparts for example self-checkouts in supermarkets, smart motorways and many appliances around the home to save time and make tasks easier which in conjunction requires more electricity. To meet the extremely high demands in electricity, power stations are built to produce power on a mass scale.

There are many different ways of producing electricity; these are categorised into two groups; non-renewable and renewable energy. Non-renewable utilises fuel like crude oil, gasses, coal and nuclear power to generate electricity [3].

These types of power station need to burn fuel to generate electricity. Currently non-renewable energy is the predominant electricity producer in the world. However this type of energy with the high demand and dwindling supply of resources are reasons for concern compelling us to look for alternatives which brings us to explore the possibility of renewable energy. Renewable energy requires the use of natural resources like water, wind, sun light, geothermal heat.

1.2 Coal power stations

The use of coal to provide power was a huge milestone achieved. The design of the first trains using coal to heat steam and push pistons; was the very first method of rotating the wheels on a train or to generate electricity. As this was the first method almost all of the power stations where built on this technology.

Coal is a form Carbon. Coal atoms are not stacked neatly, therefore making a good fuel to burn. Coal powered stations benchmarked the production of electricity; Coal is available in almost all areas of the world and is estimated to be 9.98 trillion metric tons [3].
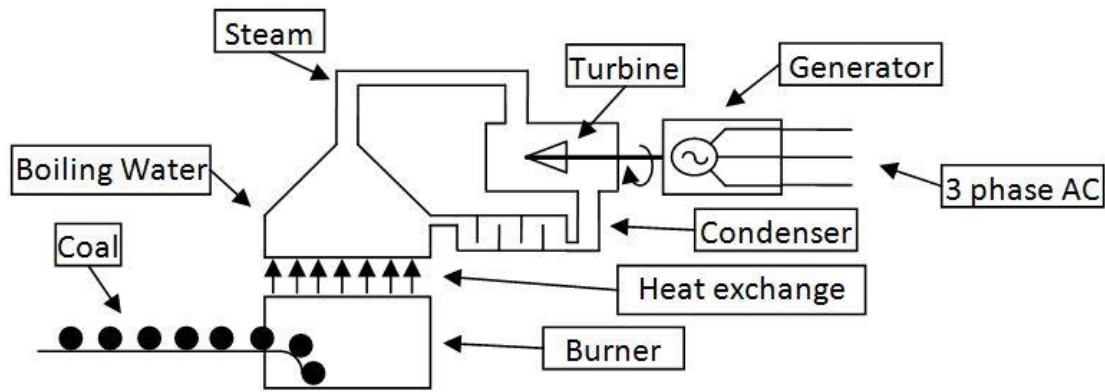
Figure 1:1: A diagram showing how coal power plant works[4]

Figure 1:1 shows how the coal generates electricity. Coal is placed in a furnace where the coal is burned to heating up water into steam. The steam then drives a turbine that is connected to a generator. This method of producing electricity has an efficiency of 40 % also 325 kg of coal is required to light a 100W light bulb for 1 year.

Burning coal has major disadvantages to the environment. The most amounts to harmful gasses for the environment come from burning coal which also causes acid rain. There is fly ash which comes from burning coal. The deposits of burned coal have chemicals like mercury, uranium, thorium, arsenic, and other heavy metals. Also there are 24,000 deaths every year and 2,800 are from lung cancer in USA [5].

1.3 Natural Gas

Gas power stations have an efficiency of 60% therefore are becoming the most popular source of non-renewable power stations[6]. Methane is used as main gas which comes from underground and under the sea floor. Open cycle gas turbine uses a gas turbine and puts its waste gas into the atmosphere as it is burned. As illustrated in Figure 1:2, combined cycle gas turbine uses the heat from the exhaust to generate steam and generate more electricity than open cycle gas turbine.
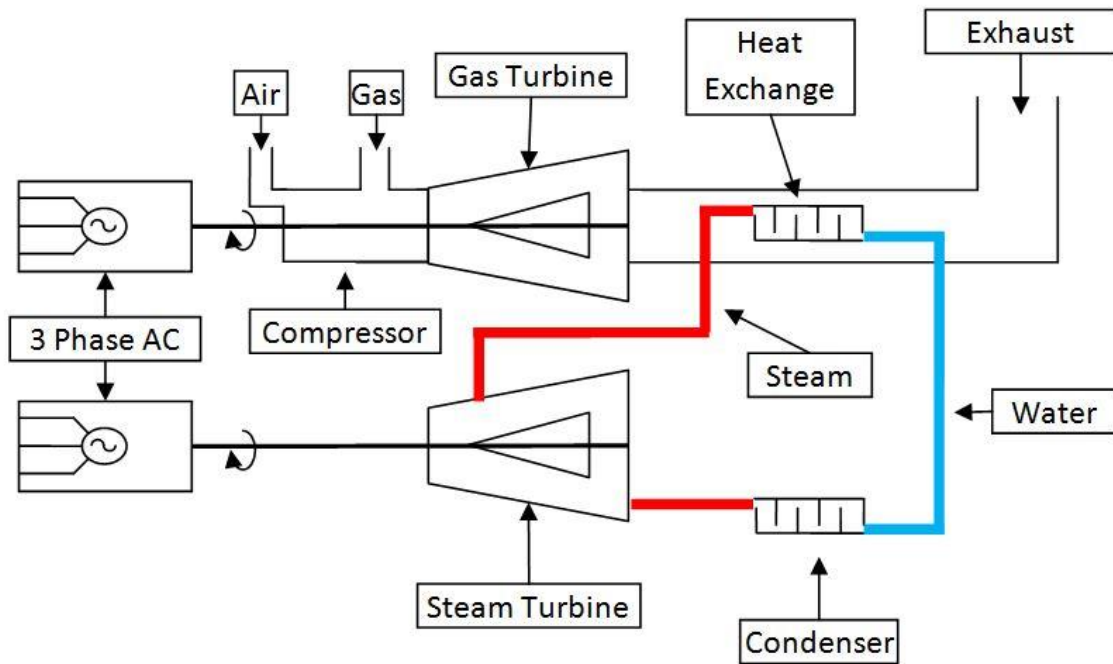
Figure 1:2: A diagram showing how a combined cycle gas turbine works [7]

Gas power stations are highly efficient. This has encouraged governments to invest into building combined cycle gas turbines, as gas can be stored when there is a high power demand. Currently there are 2693 gas power stations in the world and is capable of producing 4.2 TW. This much power is capable of providing electricity to 424 million homes. But this system requires fuel, and the fuel will cost $1,158 USD for 1 MW of electricity [7].

1.4 Nuclear power

Nuclear power plants are unique as they use a radioactive substance called Uranium in a rod rather than fossil fuels. The nuclear reaction splits an atom into two in a controlled environment which gets extremely hot. The heat is then used to boil water and the steam is used to turn the turbine. Nuclear power stations have to be built close to the coast line where a lot of water is required to cool down the system as shown in Figure 1:3.
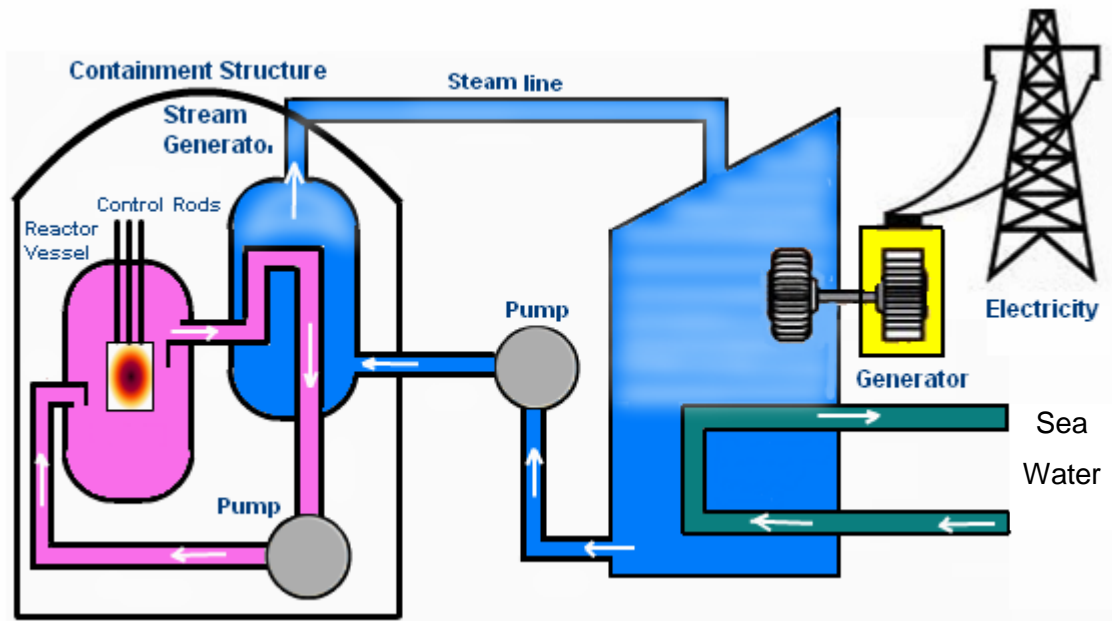
Figure 1:3: A diagram showing how a nuclear power station operates[8]

Nuclear Power plants are good because they do not contribute to global warming. However radioactive waste is expensive to dispose of. Furthermore nuclear accidents are extremely deadly; thus far there have been several cases of nuclear accidents. The Chernobyl accident has been ranked one of the worst incidents to take place; where there was a sudden power surge to one of the reactors and the shutdown procedure caused a larger spike of power. The immense pressure of steam then caused explosions sending radioactive waste into the atmosphere spreading over east Europe[9].

Nuclear power has an efficiency of 91 % and there are currently 205 nuclear power stations in 30 countries, capable of producing 1 TW of electricity [1] [2]. This much power can provide 200,000 homes with electricity for 1 year [3].

Building more power stations and using more fossil fuel is not sustainable in the current climate conditions. The continued use of fossil fuels will destroy the earth's atmosphere by putting harmful gasses. This is what causes the global warming effect which consequently affects the climate and all livings things on earth; for example the melting of ice caps raising sea levels which then causes flooding and displacing millions of people. Although renewable energy is more costly and requires more space than a power plant utilizing non-renewable energy it can improve the earth's atmosphere and produce mass amounts of power without the concern for loss of fuel. There are different ways of producing energy from natural sources; Hydro, Solar, Wind, Thermal and many more.

1.5 Hydro

Hydro power comes from water and is capable of producing electricity on a large scale. This is done by holding substantial amounts of water in water dams from large rivers. Water is controlled by a gate to allow a certain amount of water through a pipe at the bottom of the reservoir. At the end of the pipe the water is passed through a large turbine which then drives the generator producing electricity as Figure 1:4 shows.
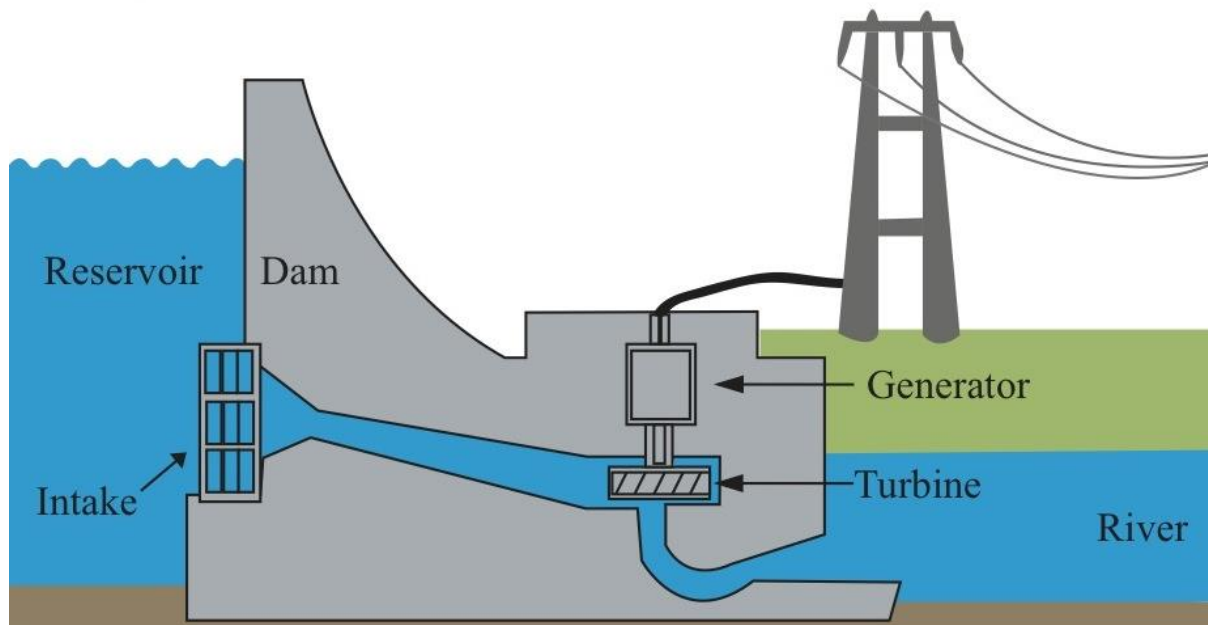
Figure 1:4: Hydro electric dam parts diagram [4]

Hydro power has many uses like production of electricity, water supply, tailing, flood control and many more. The largest hydropower electricity station is in Pakistan called the Tarbela dam and it is capable of supplying 3478 MW of electricity. Tarbela Dam is capable of proving electricity to 3 million homes which is equivalent to the size of Berlin, Germany. There are currently 3055 hydroelectric power stations producing 6.7 TW around the world. The country with the most hydro stations is the United States of America with 1309 hydro stations producing 983 MW of electricity [2]. The transfer efficiency of a hydroelectric power plant is mainly dependent on the type of water turbine in use; large installations efficiency can be as high as 95%. Whereas smaller plants that have an output of less than 5 MW may be 80 and 85% efficient. However, it can be difficult to obtain any power from low flow rates [5].

1.6 Tidal power

Tidal power generation also categorises under hydro power which is achieved by being installed off shore where the water current is high and mostly in a certain direction. The current in the water turns a set of propellers which then turn a generator. Tidal power is not a common form of producing energy as it requires a lot of time installing however only produces a small amount of power. The largest tidal station is in the Canadian waters and it produces 20 MW of electricity.

1.7 Wind

Wind turbines are frequently installed around the world, mainly on mountains and off shore. Wind blowing in certain directions helps the propellers move thereby generating electricity. This method has been derived from a similar technique used in the past for milling grain; the rotation would grind the grain into flour which would then be used in the daily bread.

The movement of air causing winds is inconsistent around the world. The higher the altitude the higher the wind speeds which is also the case near coastal lines. The jet stream, which is approximately 7-12 km above sea level, is the fastest wind speed. To take advantage of the jet streams the wind farms must be at that altitude however this option is very costly. Hence the wind farms are most commonly on the top of mountains or at coastal areas where the wind is high. As wind passes ove the mountains the pressure of the wind increases. [6].

Wind farms are mainly installed in groups to make the most of the wind in a high wind area. In order for the wind turbine to generate enough power to supply electricity the wind speed must be more than 8 miles per hour. The turbine also has a maximum wind speed rate of 45 to 80 mile per hour. This is because of the design of the propellers and gearbox. A gearbox is used to convert the wind speed to a constant speed for the electric generator as shown in Figure 1:5.
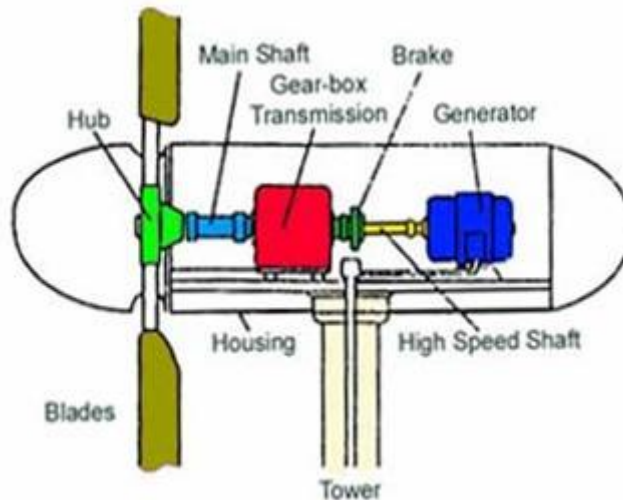
Figure 1:5: Wind turbine parts diagram [7]

There are currently 623 wind farms across the globe and are able to produce a total of 196 GW of electricity. The wind farms in world combined are capable of supplying electricity to a country like Spain. France has the highest number of wind farms totalling 289 and is able to produce 39 GW of electricity. The largest wind farm is in Texas, USA called Sweetwater Wind Farm which is capable of producing 585.5 MW of electricity [2]. Betz's law states the maximum achievable energy by a wind turbine is at about 59%.

1.8 Geothermal

Geothermal power comes from the earth .As going deep down into the ground, the earth's core gets very hot. Water is pumped down and hot steam comes back up as shown in Figure 1:6. This acts like a coal engine, heating up water and taking advantage of the steam. This power is still capable of producing Giga watts of power.
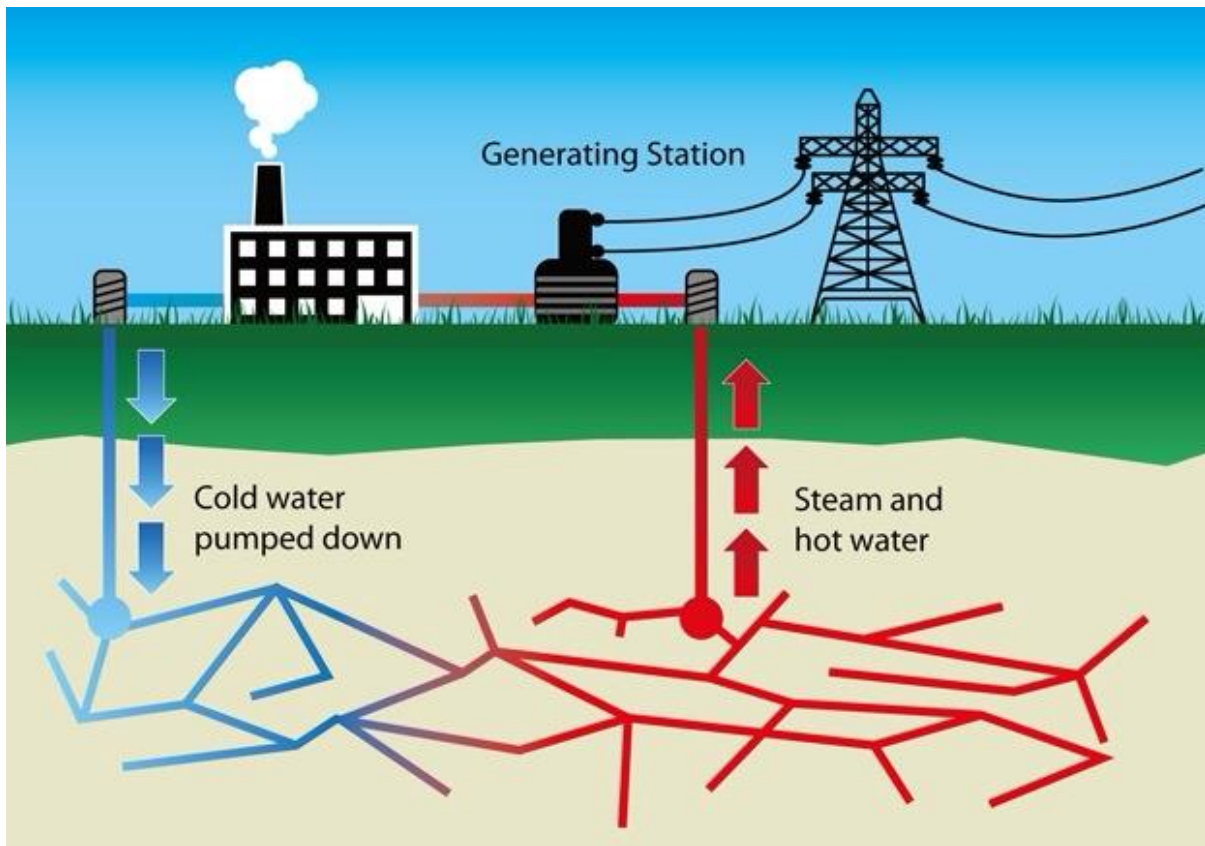
Figure 1:6: A diagram showing how geothermal works [8]

There are currently 90 geothermal power station currently operating and capable of producing 8.3 GW of electricity.

1.9 Solar-concentrated solar power

Solar concentrated energy is obtained by concentrating solar light at a single point which consequently gets hot enough to boil water. In order for this point to obtain that much heat, a series of mirrors are placed in a strategic manner so that the sun light reflected is pointed to a single place. There are a number of ways to achieve this; one form of concentrated solar power tracks the suns position and reflects the light to a projector like a large satellite dish. The heat generated at the projector can be used to run a sterling engine to produce electricity as shown in Figure 1:7 C. The second type also tracks the suns position but reflects the light to a tower Figure 1:7 B. In this technique a series of mirrors are used on a much wider scale. The top of the tower can reach temperatures of 400 ºC, this much heat is able to produce electricity in the megawatts region per day. The third type doesn't track the suns position, instead concaved mirror heats water in a glass tube. The glass tube creates a greenhouse effect where the heat enters through glass but cannot escape, therefore heating up water past boiling point. This technique uses rows of concaved mirrors and glass tubes Figure 1:7 A. A solar concentrated power station is most useful in countries close to the

equator. This type of renewable energy has a lot of potential and can easily meet the world power demands.
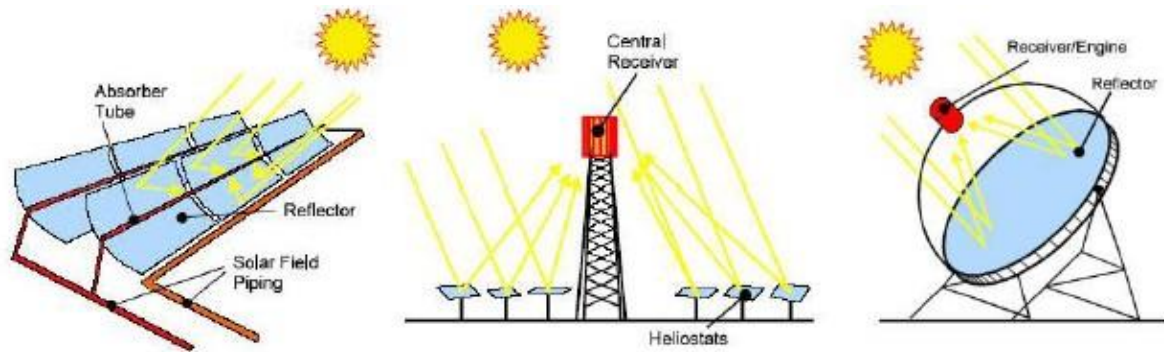
Figure 1:7: A: U-shaped mirror B: Solar tower C: Parabolic dish [9]

1.10 Solar-photovoltaic

Solar photovoltaic power converts solar irradiance directly into electricity. This type of renewable energy is the most commonly used method because it can be used on small and large scale. Small scale can be installed on the roofs of houses and buildings which are capable of producing up to 1kW power and average panel can produce 80W of power. Bridges are also being installed with photovoltaic and are capable of producing 110kW a day. Ultimately the photovoltaic farms produce the most amount of power; supplying in the Mega Watts region. On a mass scale the number photovoltaics can be increased according to the area of land available. Photovoltaics don't require any moving parts, this is advantageous as the panels could be installed on land. There are many different types of compounds the photovoltaics are made out of and more research is carried out just to make the design more efficient and cost effective.

1.11 Concentrated photovoltaic

Solar photovoltaic was invented by Alexandra hi Edmond Becquerel in 1839. Furthermore the first applications dependent on the solar power was the satellite station launched in the 1950's. The efficiency rating at this time was low as 6% and the cost was $1785 per watt. Further research has been implemented over the years to improve the efficiency and the cost to 30% efficiency and $1.25 per Watt. Around the world households are encouraged to install photovoltaics on their roof tops and any other space available to install photovoltaics. This helps the individual house hold to use the electricity during the day, which is free, and feed the rest into the mains grid, which they would be paid per unit. This is the small scale

power plants. The larger scale plants owned by farmers and companies are producing more power in the mega watts region. Governments like Germany and Spain are pushing their entire energy sectors towards the solar renewable energy.

A new plan has been introduced, if the total area of France is used in the African desert as a solar source, the entire earths power demand will be met, this plan is called Desertec. Desertec has introduced this idea and try to urge the governments to invest into the mega construction of this power plant. Once this system is up and running countries can use the electricity to convert salt water to fresh water, and they can also split the hydrogen particles from water storing the hydrogen to burn at a later stage. For example at night when there is no solar energy available or in places where the sun is not providing enough energy due to weathering. The potential for this market is great and with the correct investors the energy sector can create plenty of jobs and help with the economic crisis.

Going off the latest annual report from the EIA, currently the dominant power source is oil coal and gas. These are the non-renewable energy sources and are also harmful to the environment as they burn fossil fuels and eject harmful gasses into the earth's atmosphere. The solution to the problem is to research into renewable energy and to bring the efficiency up and invest is renewable energy. Figure 1:8 shows the different types of power stations and how much power they provided over 2011.
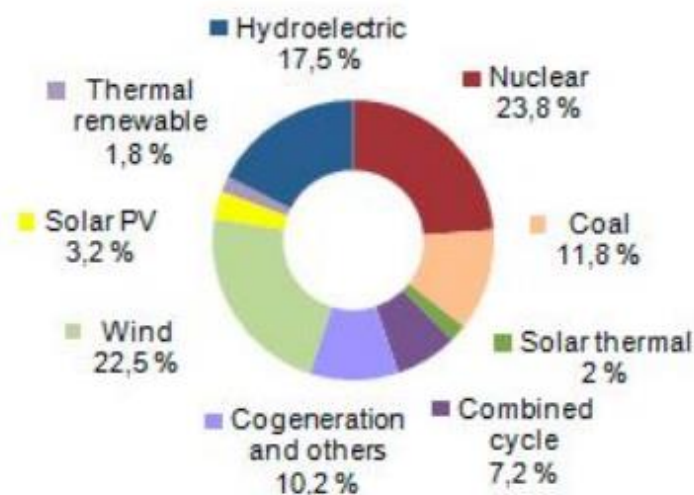
Figure 1:8: Renewable energy as share of total primary energy consumption, 2015

The Figure 1:8 illustrates what the source starts with and what step are taken to convert the source to electricity.

1.12 Aims

Fixed photovoltaic loses out on potential energy due to solar irradiance hitting them at an angle. Concentrated photovoltaic, is a way of enhancing the performance of the solar panel by following the sun trajectory. Despite that the current methods require an extra energy consumption to move the photovoltaic panels as they track the sun. In addition, the current tracking systems are not detecting efficiently the real maximum power point. Therefore the existent maximum power point tracking methods need to be further optimized.

To overcome these problems, the design of an irradiance and power tracker to gain optimum energy levels will be investigated.

1.13 Objectives

The problem will be split into two research studies:

1) Solar tracking system design study

A design of the concentrated photovoltaic that can track the most amount of irradiance efficiently will be studied together with the sensing system that can detect the direction of the most amount of irradiance.

2) Study of maximum power point tracking algorithms.

The maximum power point with multiple peaks of power when partial shading occurs can be obtained through a microcontroller that can find the global peak. Two most commonly used algorithms are applied to a converter unit of solar system to stay at the global power peak. A comparative analysis was also carried out to establish the accuracy and efficiency of the system which does not require a lot of processing power.

2   Literature review

Solar panels can have many uses like powering caravans, mobile phones, water pumps, house hold appliances, street lighting parking meters and many more. These solar panels are mainly facing in a fixed direction and can also have shading effects. The main purpose of this research is optimize the existing panels to harness more potential energy from the sun.

There are many algorithms to track the maximum power point; these algorithms can also track partially shaded photovoltaic panels. The algorithms read the power coming out of the photovoltaic and consequently compute the direction of the maximum power point. Each algorithm uses different techniques to track the maximum power using a DC to DC converter to control the power. Some algorithms do not use a DC to DC converter; they physically switch the modules around to obtain the optimum power. The comparison of Perturb and observe along with Incremental Conductance will reviewed along with other algorithms.

2.1 Perturb and observe

This is the most commonly used algorithm for maximum power point tracking. This is due to the fact that it is very easy to program and setup. This algorithm can be executed on almost any microprocessor because it only controls the DC to DC converter via a PWM signal.

This program takes two samples of the current and the voltage next to each other and then determines the direction of the first power peak. Once the maximum power point is achieved the power starts to drop, that is how the systems knows it has reached the maximum power point.
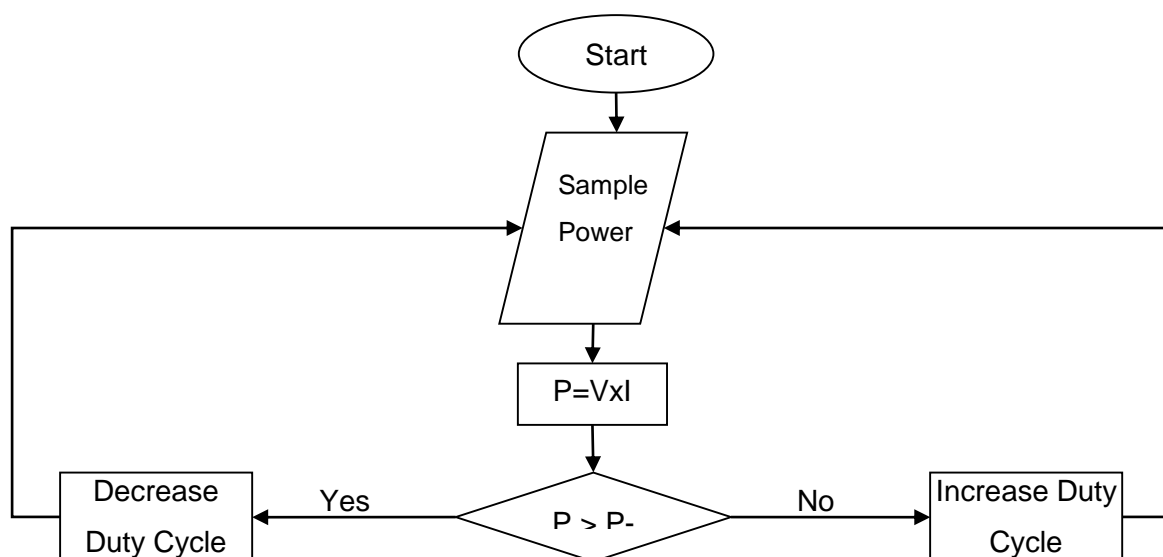
Figure 2:1: Flowchart of perturb and observe algorithm working principle

Looking at flow chart in Figure 2:1, the program has an infinite loop and will keep on tracking the maximum power point. Also the duty cycle will always change regardless of the difference in the two power readings. A DC to DC converter uses a switch to rapidly turn on and off to control the voltage, the duration of the switch being on over off is called the duty cycle that can be controlled by algorithms. The program will lose power because it will oscillate around the maximum power point and not specifically at the maximum power point.

The implementation of this technique is fairly simple as it does not require use of much hardware. Also if there are multiple peaks of power this algorithm will only find the first peak of power regardless of whether there is more power available at a higher voltage. Moreover as this algorithm hovers around the maximum power point, there is a lose of power.

Implementation and cost are low, making this the most commonly used algorithm. The losses due to hovering around the maximum power point can be reduced by decreasing the duty cycle step. If the system has a large sampling size to start off with, it may obtain the maximum power point as fast as possible, then the step size can be reduced to a smaller one. The power losses of the algorithm will be reduced. [10] [11].

2.2 Incremental conductance

Incremental conductance is the second most used algorithm in the industry. Just like P & O it is very easy to implement and almost any microprocessor is capable of running the code. This program will take two samples and will look at the slope of the power. If there is a positive slope the maximum power point will be to the right. If the slope is negative the maximum power point will be to the left. But if the slope is constant the system has reached the maximum power point as illustrated in Figure 2:2.
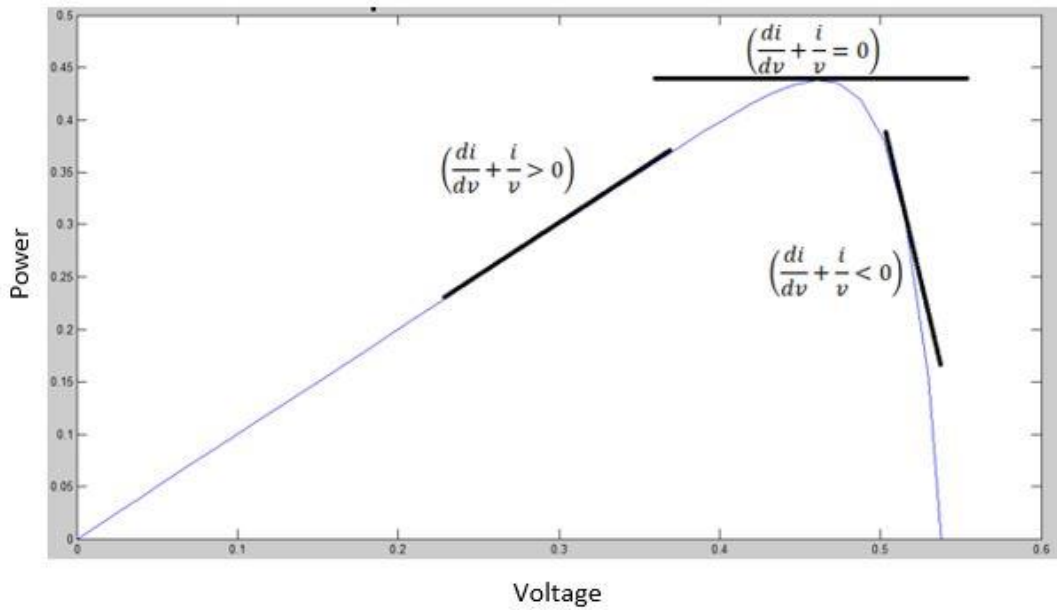
Figure 2:2: A graph showing how incremental conductance identifies the maximum power point

This technique measures the slope and then computes the maximum power point. It measures a certain point then measures a step to the right of it to determine the I-V curve at this point. The slope subsequently determines the direction of the maximum power point. If there is a positive slope, the maximum power point is at the right of this certain measured point. If there is a negative slope, the maximum power point is to the left of the measurement. This process is repeated till the maximum power point is found when the gradient is zero. The Mathematical representation is as follows:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V}$$

At maximum power point the gradient is zero

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V}$$

To the left of maximum power point because there is a negative gradient

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V}$$

To the right of maximum power point because there is a positive gradient

This technique measures the slope and determines the direction of the maximum power point. It will then alter the duty cycle of the PWM which will alter the voltage to get to the maximum power point. The flow code in Figure 2:3 is the skeleton of how the algorithm works.

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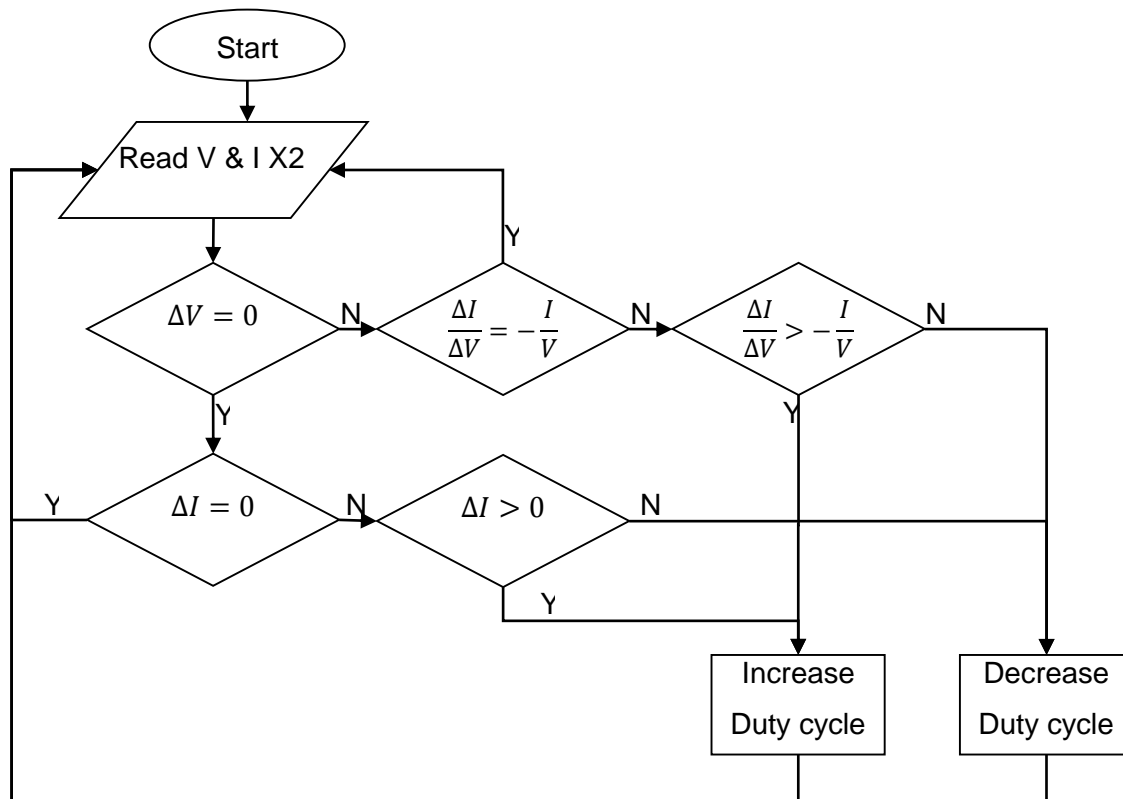
Figure 2:3: A flow chart showing how the incremental conductance algorithm works

Advantages:

- Easy to implement
- Big step size can reach the maximum power point faster

Disadvantage

- The output can be around the maximum power point not at the maximum power point
- A smaller step size can get an accurate maximum power point but it will take longer to get to.

The incremental conductance technique uses a step size, which determines the speed to reach the maximum power point. The bigger the step size the faster the maximum power point will be obtained. A small step size will give you a more accurate maximum power point. So in conclusion the step size must not be too big or too small [12].

2.3 Ripple correlation control

Ripple correlation control is mainly used to control switching topologies. This method uses the output of the switching in the DC to DC converter to track the maximum power point.

The DC to DC converter will switch on and off at a certain frequency, which will cause a ripple on the output of the PV array. The method used here will look at the ripple in time derivate power (*P)* in correlation to the time derivative current (*i*) or time derivative voltage (*V*) to drive the gradient to zero as illustrated in Eq (2.1). If the power (*P*) is increasing the maximum power point is not achieved and it will keep rising. If the voltage (*V*) is increasing and the power is decreasing the maximum power point is on the left.

$$d(t) = -k \int PV \ dt \text{ or } d(t) = k \int Pi \ dt$$

Eq (2.1)

The formula displayed above shows k is a positive constant to control the duty cycle, if the constant voltage is increased the duty cycle increases and vice versa. This system requires a very fast analogue to digital conversion for the voltage and the current, therefore it will increase the cost of the hardware; the microprocessor must also be fast in order for it to see the ripple [13].

2.4 Fibonacci search

The Fibonacci sequence is a number sequence. The numbers start at zero and one, the next number is determined by the sum of the previous two numbers.

$$F_n = F_{n-1} + F_{n-2}$$
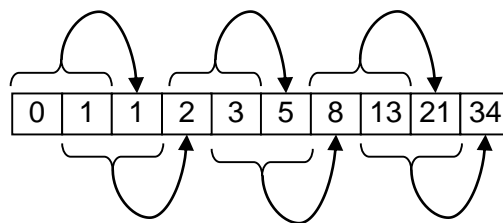
Eq (2.2)

The Fibonacci sequence uses the numbers to focus into the maximum power point as the numbers increase. The algorithm takes samples of the power of the Fibonacci sequence, so at voltages: 0, 1, 2, 3, 5, 8, 13, 21, 34 etc. The highest peak of power is then determined according to the sampled voltages, however this is not the maximum power point. The highest peak is marked close to the maximum power point; the algorithm then uses the perturb and observe algorithm to achieve maximum power point [14].

The power is measured by the left and the right of the highest peak. The higher voltage is taken into consideration and the process is repeated until the maximum power point has been achieved. This process will be repeated to stay at the maximum power point.

This method does skip the bulk of the sampling because it only samples in the Fibonacci sequence. The Fibonacci sequence is used at the start of the system. For the rest of the

process the algorithm Perturb and Observe is used with a larger step size. This means the system is hovering around the maximum power point which loses a little power.

2.5 Fuzzy logic algorithm

Fuzzy logic is a generic algorithm that is widely used for all sorts of solar power tracking applications. It uses a technique where the algorithmic part is categorised into sections. These sections consequently determine the output. Fuzzy logic carries out 4 steps to identify the problem:

1. Establishing the categories
2. Evaluation
3. The results
4. Converting from fuzzy logic output to original outputs

When the problems have been identified for example, for maximum power point tracking the problem is to find the maximum power point and where the boundaries are to achieving the maximum power point [15].

Fuzzy logic technique samples two points very close together to obtain the gradient. Fuzzy logic uses 5 classifications to determine the maximum power point; following is a list of the classifications:

1. Negative big
2. Negative small
3. Zero
4. Positive small
5. Positive big

If the gradient is more than ± 0.5 W it is considered to be a big gradient. If the gradient is less than ± 0.5 W the gradient is considered small.

This system is a bit more complicated to implement. Its fundamental technique closely follows incremental conductance algorithm as it determines the gradient first then computes the location of the maximum power point.

2.6 Artificial neural network

The Artificial Neural Network algorithm is widely used in all sorts of application. This is algorithm based on the human mind. The inputs are applied and the desired outputs are programmed according to the inputs. The system needs to be taught the relationship

between the input and the output. Once this relationship is learnt the algorithm is able to execute when the same scenario occurs.

Inputs   Hidden   Outputs
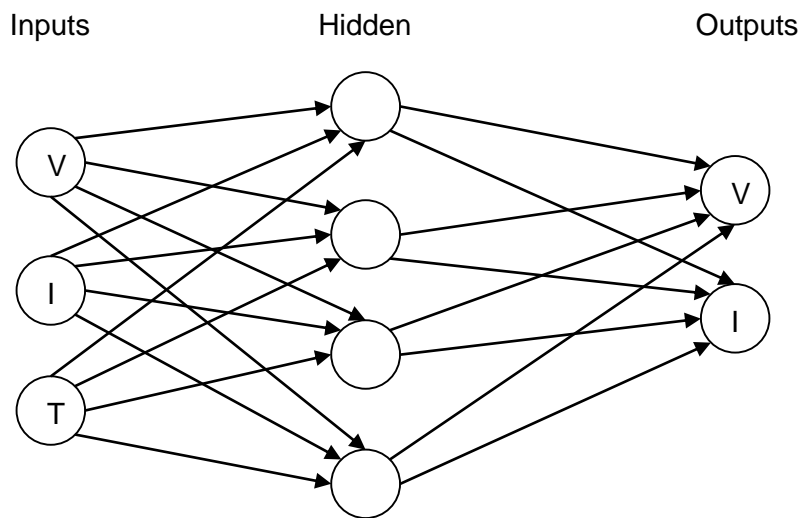
Figure 2:4: State diagram showing how neural network operates

The diagram in Figure 2:4 shows how the skeleton of the artificial neural network works. The hidden layer is where the system learns the algorithm. In this case the learning process would be to find the maximum power point with the inputs provided and every single scenario is programmed [16].

This method is time consuming as the system needs to train in all possible outcomes. Since each photovoltaic system is different the algorithm has to be trained to adapt to each system individually.

2.7 Su Do Ku algorithm

Sudoku is a number puzzle that consists of a 9x9 grid which is split into 3x3 boxes, each 3x3 box, row and column must contain the numbers 1 to 9 without repeating any digit. This method connects the solar modules like the numbers of a Sudoku puzzle. One Sudoku puzzle is chosen to use as a guide to set up the system, if a few modules are shaded the effect will be spread out equally throughout the rows and columns of the overall system [17]

Looking at Figure 2:5 the position of the solar module is physically connected in another location. For example the first row second column is connected at the fourth row second column. Therefore if the top left of the panel, including the first row second column, was to be shaded the effect of it would show on the fifth row hence evenly spreading the shaded modules across the panel.
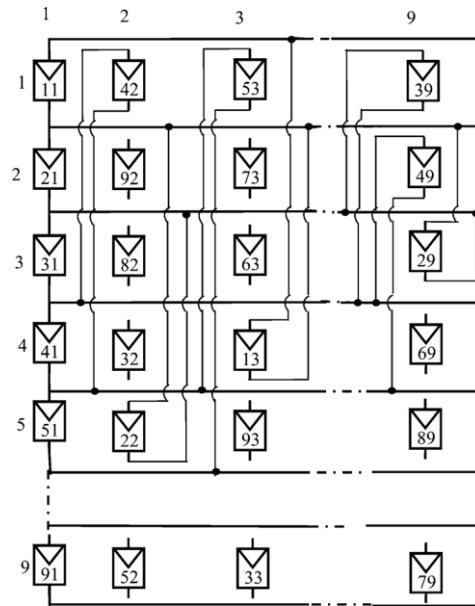
Figure 2:5: Sudoku connections

In the research carried out by Di Vincenzo, M. C. [17], the local peaks have been eliminated and only left with a single peak. In some cases this system will not work for example, if the shading is not together or is unevenly spread out there still would be multiple peaks of power.

2.8 Electrical array reconfiguration

This method has individual PV modules and measures the power from each module individually. The algorithm connects all the modules that have the same amount of power together in a row. This means the module will not supply another module on the same row.

The current is added once the modules are placed in series and the voltage is kept constant for all the modules in that row. Therefore if there are 9 modules they can be rearranged to have 3 rows and 3 modules in each. Or even one row with 5 modules and one with 4 modules. As long as each row has the same average power [18].

There is a lot of measuring equipment installed, for each module a voltmeter and a current meter is required, which can be implemented for every module or even every photovoltaic panel. This technique is better described as a way of connecting modules to deliver the maximum power point like the Sudoku algorithm, however the Sudoku algorithm does not switch the modules as they are hardwired.

2.9 Fractional short circuit current or fractional open circuit voltage

Since the I_{sc} is known and can be measured the operational I_{MPP} range can be predicted to a certain extent. This program creates a short circuit by connecting a MOSFET to the terminals of the photovoltaic and measures the current through it when switched on. This provides the information required to obtain the operational I_{MPP} range. The program adjusts the duty cycle so the system operates in that region.

The fractional open circuit voltage computes the maximum power point in the same manner as fractional short circuit current. As the V_{oc} range is known the system stays within that range to obtain the maximum power point [19].

These algorithms are not accurate enough as they assume there are no local peaks of power or they go near to the maximum power point and not at the maximum power point [19].

2.10 Comparison

There are currently over 90 algorithms to find the maximum power point [19]. Each algorithm works in a very similar manner in terms of hardware. Following is a list of some of the more commonly used algorithms:

- Differential Evolution
- Stochastic algorithm
- Dividing rectangles optimization-DIRECT
- Dc link capacitor droop voltage
- Best fit voltage
- Model based control
- Line search
- Newton Ralph
- Curve-fitting technique
- Look-up table
- One cycle control
- Forced oscillation technique
- Current sweep technique
- Parasitic capacitance technique
- Hybrid maximum power point tracking

Table 1 shows the performance and issues of each algorithm. It also demonstrates how easy it is to implement the algorithm with the hardware and what the speed of the tracking is.

MPPT Technique	PV Array Dependent?	True MPPT?	Analog or Digital?	Periodic Tuning?	Convergence Speed	Implementation Complexity	Sensed Parameters
Hill-climbing/P&O	No	Yes	Both	No	Varies	Low	Voltage, Current
IncCond	No	Yes	Digital	No	Varies	Medium	Voltage, Current
Fractional V_{OC}	Yes	No	Both	Yes	Medium	Low	Voltage
Fractional I_{SC}	Yes	No	Both	Yes	Medium	Medium	Current
Fuzzy Logic Control	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural Network	Yes	Yes	Digital	Yes	Fast	High	Varies
RCC	No	Yes	Analog	No	Fast	Low	Voltage, Current
Current Sweep	Yes	Yes	Digital	Yes	Slow	High	Voltage, Current
DC Link Capacitor Droop Control	No	No	Both	No	Medium	Low	Voltage
Load I or V Maximization	No	No	Analog	No	Fast	Low	Voltage, Current
dP/dV or dP/dI Feedback Control	No	Yes	Digital	No	Fast	Medium	Voltage, Current
Array Reconfiguration	Yes	No	Digital	Yes	Slow	High	Voltage, Current
Linear Current Control	Yes	No	Digital	Yes	Fast	Medium	Irradiance
I_{MPP} & V_{MPP} Computation	Yes	Yes	Digital	Yes	N/A	Medium	Irradiance, Temperature
State-based MPPT	Yes	Yes	Both	Yes	Fast	High	Voltage, Current
OCC MPPT	Yes	No	Both	Yes	Fast	Medium	Current
BFV	Yes	No	Both	Yes	N/A	Low	None
LRCM	Yes	No	Digital	No	N/A	High	Voltage, Current
Slide Control	No	Yes	Digital	No	Fast	Medium	Voltage, Current

2.11 Partial shading

There are a few types of algorithms to find the maximum power point when partial shading occurs. One type of algorithm scans the entire PV-curve from the lowest possible voltage to the highest possible voltage, and then selected the duty cycle at the global peak. Usually this is repeated after certain time or if there is a change in the conditions. The algorithms efficiency will decrease because the system is busy scanning the PV-curve and potential power is lost. Each time the duty cycle is updated the power is measured and stored in the microcontroller; the algorithm then finds the maximum value. With this system the microcontroller used has to have a high speed processor with enough memory to accommodate all the readings. Figure 2:6 illustrates how this type of algorithm operates. The power curve shown in red is the partially shaded photovoltaic. The black line indicates the scanning process that the algorithm will adjust via the duty cycle. This method directly find the global power peak, to keep track of the global power peak the algorithm will use the conventional perturb and observe or incremental conductance.
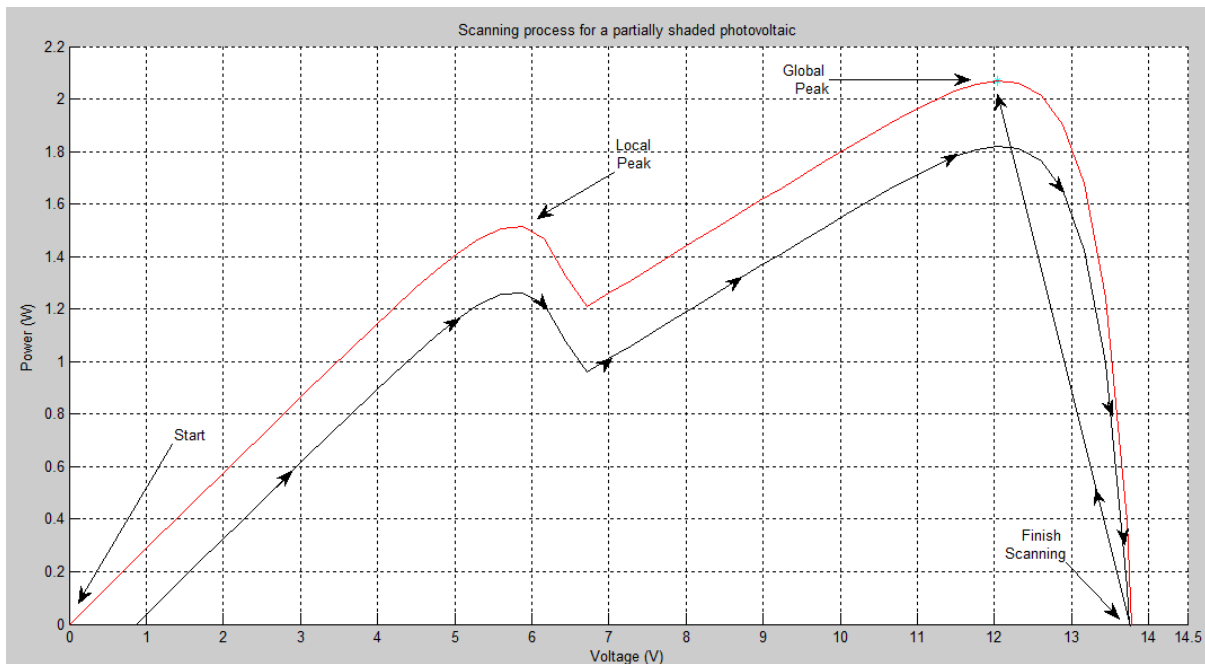
Figure 2:6: A graph showing a partially shaded power curve and the scanning process

The second system samples the power at specific points and then determines which reading is the highest. Once the maximum reading has been determined the algorithm will look at which side has more power. This method is very similar to the scanning method but the step size is much larger. Figure 2:7 has the identical power curve to Figure 2:6 but Figure 2:7 uses a sampling approach. The samples are different points, like the first and second sample will be at highest and lowest duty cycle. The rest of the samples are different duty cycles. This finds the global power peak much faster as it not consistently gathering data as the duty cycle is increased. Once the largest peak has been found, in this case the 6th sample, the system needs to narrow into the global peak. This could be on the left or the right of the sample. So the conventional perturb and observe or incremental conductance can find the peak and keep track of it.
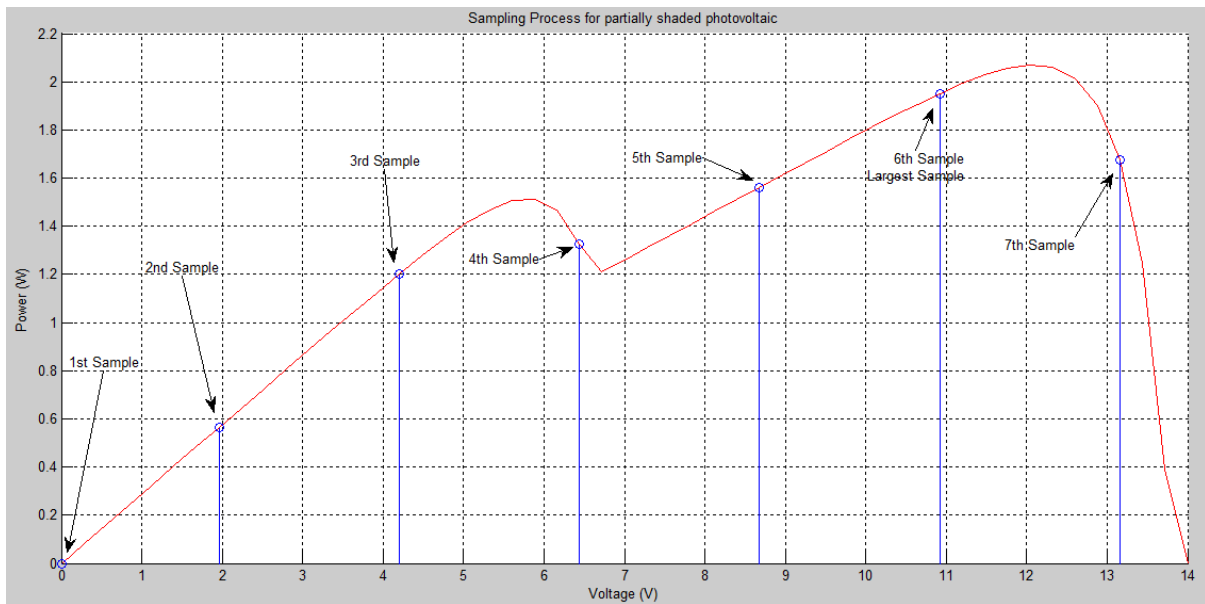
Figure 2:7: A graph showing a partially shaded power curve and the sampling process

Another method is to modify existing algorithms to find the global peak. These algorithms require more information like the open circuit voltage, the number peaks that the photovoltaic system can have and the number of photovoltaic cells in the entire array. With this information the system can find each peak using the modified algorithm and go to the global peak. In [20] the algorithm incremental conductance is modified to accommodate 3 peaks of power and load variation. So the algorithm can find the global peak and control the converter according to the load. As conventional incremental conductance operates the first peak is found, the modified version works the exact way but compares the first peak to the second and third. If the rest of the peaks are zero the algorithm will increase the duty cycle to find the next peak.

2.12 Summary and Importance of this research

There has been a rise in the renewable energy sector due to the limitation of fossil fuels and they are more harmful to the environment. The solar photovoltaic is a unique way of producing energy as it converts the suns light directly into electricity. With sunlight available all around the world, during the day. This is a sector where the future is heading due to low barriers to entry. However power coming from the photovoltaic is currently not at its maximum potential, for example parking meter panels are fixed and over shadowed at times by trees or high buildings. Most of the photovoltaic panels are at a fixed angle, the potential power available is lost due to solar irradiance reaching the photovoltaic at an angle. A series of sensors can measure the maximum amount of light available and then control some motors to obtain most light for the photovoltaic. This way the motors are not constantly using

25

energy to move the panels' angle and direction but are moving when there is a real need to move the panels' angle or direction. A literature review of current solar tracking systems and power tracking algorithms was made in this chapter to outline their advantages and disadvantages. A detailed description of how the solar panels work and how these algorithms are implemented is given in chapter 3. Chapter 4 explains the system modelling and simulation while the system design and the results are reported in chapter 5. The conclusion is given in chapter 6, with further considerations for future work.

Materials and Physical structure of a solar cell

This chapter contains the theoretical analysis of the photovoltaic. This details from the physical structure and different materials used in manufacturing and how this impacts the performance. On a more technical note this chapter will explain the different ways of obtaining the efficiency and the different ways of connecting the modules and how it effects the efficiency.

2.13 Raw materials

The photovoltaic materials are made out of pure silicon, but silicon is not pure in its natural state. Pure Silicon can come from Quartzite gravel or crushed Quartz. The charged materials are heated in an electric arc furnace. This leaves carbon dioxide and molten silicon. This is then doped with Boren and Phosphorus which looks like the image in Figure 2:8. The silicon is then cut into wafers with a thickness of 275 μm to 925 μm. The silicon wafers get an anti-reflective coating of titanium dioxide to reduce the shine [21].

Figure 2:8: Silicon ingot and silicon wafers [21]

Figure 2:8 shows pure silicon before it is cut into wafers. To cut the silicon into equal pieces the ends are cut off and discarded as waste. The wafers are then cut to nanometre precision. The wafers then look like Figure 2:8. These wafers are then heated just enough so the phosphorus elements to embed into the wafers.

2.13.1 Purifying the silicon

Photovoltaic use 100 % pure silicon, this silicon is extracted from Quartzite gravel or crushed Quartz. The silicon dioxide of the compounds is placed in an electric arc furnace. The

oxygen is released by applying a carbon arc. This leaves carbon dioxide and 99 % pure silicon.

2.13.2   Making single crystal silicon

The 99 % silicon is heated and a process called Czochralski method is used to extract the pure silicon. Czochralski method uses a seed crystal that pulls and turns at the same time. This makes a solid cylindrical ingot, as shown in Figure 2:8; this is also 100 % pure as the impurities are left behind in a liquid form

2.13.3   Making silicon wafers

The silicon ingot has two cones on each end of the ingot; these cones are cut off so there is only a cylinder left. A wire saw is used to cut through the ingot cylinder to make wafers of 0.5 mm thickness.

2.13.4   Doping

The doping process is to add phosphorus and Boren to the silicon wafer. This will allow it to conduct electricity.

A diode is manufactured in the same manner. In fact the photovoltaic is the exact opposite of a light emitting diode. When voltage is applied to a light emitting diode the depletion layer produces a light. For the photovoltaic the light is required for the P type to travel towards the N type.

2.14 Materials

Mono-crystalline: the atoms in this type of silicon form a continuous regular lattice throughout an entire solid. Its regular structure is a means for its superior response rate. The high purity atoms in this silicon are unmistakable as they have an even external colouring and uniform look.

Advantage:

- Due to the fact that that they are made out of highest grade silicon they have the most premium efficiency rates; typically at 15 – 20%
- Most space efficient, although generating the highest power outputs require the least amount of space in comparison to all other types. In comparison to thin film solar panels they are able to produce up to four times the amount of electricity.
- For the most part have better performance in low light in comparison to polycrystalline solar panels.

Disadvantages:

- Expensive
- Being partially covered by shade, dirt or snow can cause the entire circuit to malfunction. If this is a possibility, micro inverters may be considered instead of central string inverters; which can potentially stop the whole solar array from being effected.
- Optimum performance is achieved at warm temperatures, as temperature goes up the solar panels efficiency suffers.
- Uses the Czochralski process, this process has significant amount of waste of the original silicon.

Poly-crystalline: these are the first crystalline silicon based solar panels created and were introduced in 1981. As these solar panels do not require the use of the Czochralski process they are simpler to manufacture.

Advantages:

- Simpler method used to create therefore more cost effective
- Polycrystalline solar panels have a lower heat tolerance in comparison to monocrystalline solar panels.

Disadvantages:

- Typical efficiency at 13 – 16%, which is not nearly as efficient as the monocrystalline solar panel
- Low space efficiency, a large surface area must be covered to output a similar amount of electrical power in comparison to the monocrystalline solar panels.

Thin-Film Solar Cells (TFSC): Solar thin film is manufactured by depositing thin layers of photovoltaic material. There are different types of thin-film solar cells that can be categorized by different photovoltaic materials used:

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIS/CIGS)
- Organic photovoltaic cells (OPC)

Prototypes are known to reach an efficiency of 7 – 13 % whilst production modules operate at about 9%. The aim for future module efficiency is 10 – 16 %.

Advantages:

- Simple mass production therefore potentially cheaper to manufacture
- Has much potential due to the fact that they can be made flexible
- Performance is not affected by high temperatures and shading as much it is with other solar panels

Disadvantages:

- Although thin-film solar panels are cheaper they require space therefore aren't very useful in residential areas
- Thin film solar panels degrade faster than Mono and poly crystalline solar panels [22].

2.15 Physical structure of a solar cell

The solar cell converts light energy directly into electricity by the photovoltaic effect. The current that is generated by the solar cell is dependent on the amount of solar irradiance. A solar cell has a layer of P type silicon on top of N type silicon just like a diode. When the solar irradiance hits the solar cell the Positive charge moves to the Negative causing a current to flow [23].
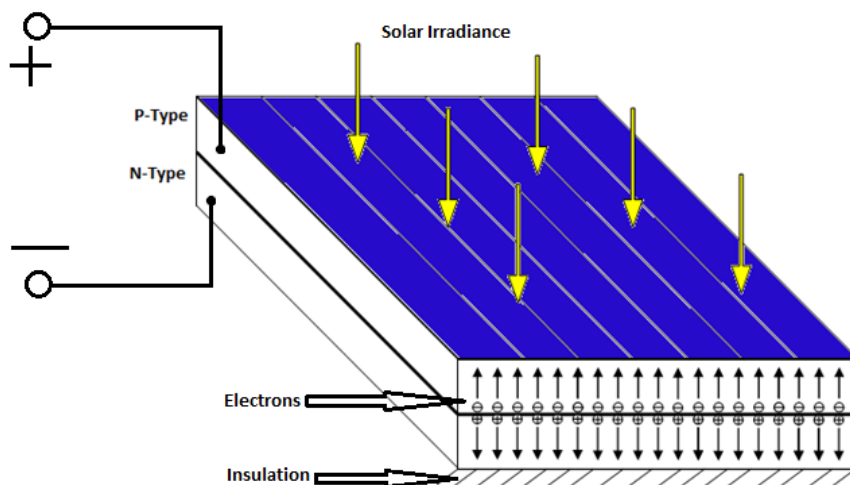
Figure 2:9: Shows how the electrons move when the solar irradiance is applied
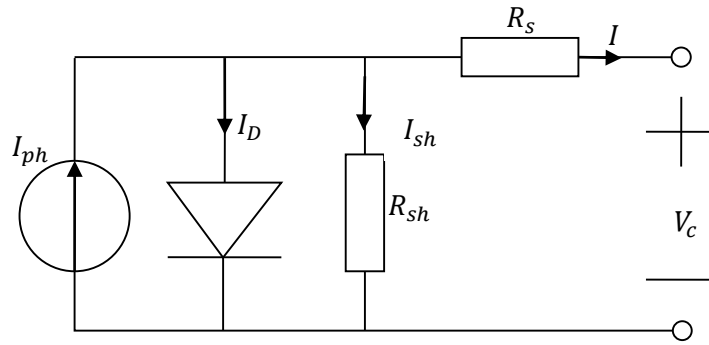
Figure 2:10: Model of a single solar cell

Figure 2:10: model contains a diode and a current source I_{ph} in series with resistor R_s, the resistor in series R_s is also known to be zero ohms. The difference between the photocurrent and the diode is given by:

$$I = I_{ph} - I_D - I_{sh}$$

Eq (3.1)

Where I_{sh} is:

$$I_{sh} = \frac{V}{R_{sh}}$$

Eq (3.2)

Where I_D is:

$$I_D = I_S \left(e^{\frac{qVd}{nkt}} - 1 \right)$$

Eq (3.3)

For normal room temperature:

$$\frac{kt}{q} \approx 25mV = V_T$$

Eq (3.4)

Therefore :

$$I = I_S \left(e^{\frac{Vd}{nV_T}} - 1 \right) - I_{ph} - \left(\frac{Vd}{R_{sh}} \right)$$

Eq (3.5)

q Is electronic charge

n Is the idealising factor

k Is the Boltzmann's gas constant $(1.380 * 10^{-23} m^2 kgs^{-2}K^{-1})$

T_c Is the Cell Temperature [23]

2.15.1   Short circuit current

The short circuit current is taken when there is no load on the photovoltaic; this is achieved by connecting the positive and negative to each other through an ammeter. The short circuit current is determined by the amount of irradiance, as the irradiance increases, the short circuit current also increses [23].

$$I_{SC} = I\left(e^{\frac{Vd}{nV_T}} - 1\right) - I_{ph} - \left(\frac{Vd}{R_{sh}}\right)$$

Eq (3.6)

2.15.2   Open circuit voltage

The open circuit voltage is obtained by connecting the positive and negative together through a voltmeter, this would mean the current is zero. The open circuit voltage is determined by the temperature of the solar cell, the higher the temperature the lower the open circuit voltage.

The expression to determine the open circuit voltage is as follows [23]:

$$V_{oc} = \frac{nkT_c}{q} \, ln\left(\frac{I_{ph}}{I_o}\right)$$

Eq (3.7)

2.15.3   Dark current

A current forced to pass through a shaded solar cell is referred to as a dark current. This helps determine the ideality factor and the saturation current of the diodes. This is to help establish how much current one solar cell can handle. When the current is passed though the solar cell the equivalent resistive loads can be determined, this is given by equation 3.2.

The dark current can also relate to a conventional diode. Figure 2:11 shows how diode current will relate to a photovoltaic with light and without light. Without light the photovoltaic will act exactly like a diode when a current is passed through. With light it would become a current source.
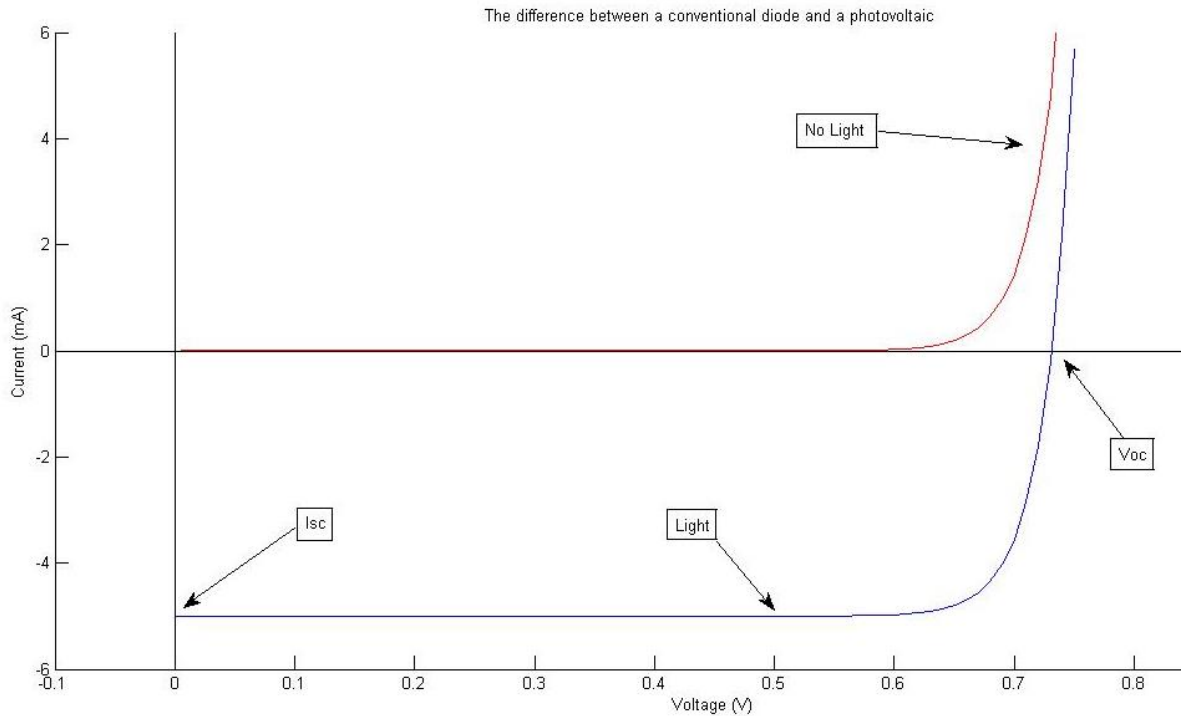
Figure 2:11: The difference between normal diode verses a photovoltaic

2.15.4   I-V curve

The I-V curve can be useful information as it shows what the current is at different voltages. The power curve and the maximum power can then also be derived from this information.

A resistor is placed along with a voltmeter on the terminals of the photovoltaics as shown in figure 3. Slowly increase the resistance and check the voltage across the resistor, in series an ammeter can be placed. This will give you the information on voltage, current and resistance. The range of the resistors used can be from 0 Ω (short circuit) to about 3 KΩ. The resistance is generally increased in steps of 100Ω till the current goes very close to zero, which is the open circuit voltage

2.15.5   P-V curve

This information is the most important information required of a photovoltaic system. This is because maximum power can be obtained from this information. I-V curve can be obtained whereas the P-V curve has to be calculated. The current is multiplied by the voltage. This will give a single peak of power.

For high powered systems that produce power on a mass scale use DC to DC on a buck convertor. A buck convertor is used to vary the voltage, so the current can be measured as shown in figure 3 on the right.
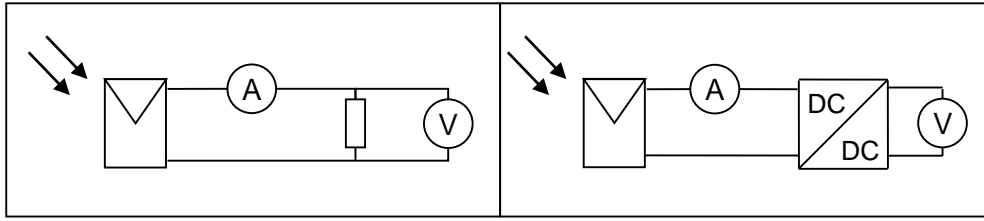
Figure 2:12: Circuit diagrams
A: small scale   B: Large scale

2.15.6   Fill factor

The Fill Factor is sharpness of the knee in the I-V curve. The fill factor can be calculated by the open circuit voltage, short circuit current, the current and voltage at maximum power. The equation is given:

$$FF = \frac{I_{mpp}V_{mpp}}{v_{oc}I_{sc}} \text{ [23]}$$

Eq (3.8)

The larger the fill factor the higher the efficiency of the solar cell.

2.15.7   Efficiency

The efficiency is determined by the power in and power out. In the case of photovoltaic array the input power is measured in solar irradiance set on the photovoltaic panel. The efficiency given by:

$$\eta = \frac{P_{max}}{P_{in}} \text{ [23]}$$

Eq (3.9)

Where P_{in} irradiance in is Wm^{-2} multiplied by the area of the solar cell in m^2. The Power max is the current and voltage at power maximum power.

$$\eta = \frac{I_{Max} \cdot V_{Max} \cdot FF}{Irradiance\ Wm^{-2} Area\ m^2} \text{ [23]}$$

Eq (3.10)

A typical solar cell is a couple of millimetres in size and will provide approximately 0.5 watts. Multiple solar cells are connected in parallel and series.

When a solar cell is connected in series it will add the voltages of each cell; however when the rows of solar cells are connected in parallel the current is added. A few hundred solar

34

cells are connected in parallel series which is known as a photovoltaic module, these modules are furthermore connected into a parallel series to compose the photovoltaic module.

2.15.8   Solar irradiance and temperature effect

Solar irradiance is a measurement of how much sun light is at the earth's surface in power per unit area. The maximum power that can be available like in the Sahara desert the irradiance can go up to 1000 watts per 1 meter squared. This has an effect on the current, the more the solar irradiance the more the current as shown in Figure 2:13.
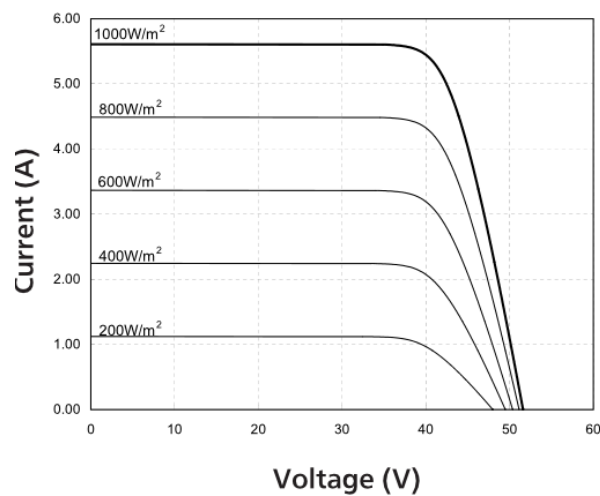
Figure 2:13: Solar irradiance effect on solar cell [24]

The temperature is given in equation 3.4. The more the temperature the less the v_{oc}, the efficiency of the photovoltaic decreases as the cell temperature increases as shown in Figure 2:14.
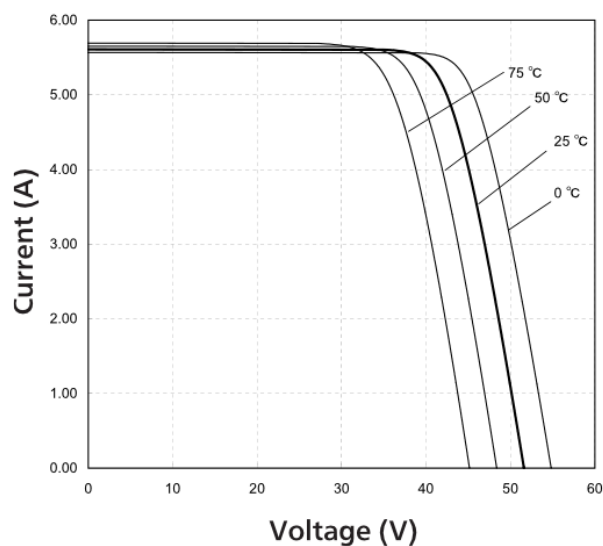
Figure 2:14: Temperature effect on solar cell [24]

Photovoltaics are current sources because the current responds to the amount the light on the solar cell. However, the photovoltaic will not provide infinite voltage and a constant current no matter what the load correspond to. The photovoltaic has a limit where the current will start to drop, but the solar cell will become a voltage sink. This happens when the voltage across the diode exceeds 0.7 V. This means the diode has switched on and all the current is now flowing through the diode, hence the solar cell becoming a voltage sink. So with this information, the maximum power available from a single solar cell is just before the diode switches on.

2.15.9 Photovoltaic array

A solar cell is minuscule therefore many cells are placed together in a series to obtain an ample amount of voltage. Subsequently an equal number of solar cells are connected in parallel columns to help increase the current, thus a solar module is completed. The modules are similarly connected in a parallel series to make one photovoltaic panel. A typical 80W photovoltaic panel will have approximately 32 modules.

Each module will have a bypass diode in case of partial shading. If one module is shaded it becomes a load for the rest of the panel. The solution to this problem is that each module has a bypass diode as shown in Figure 2:15. If too many solar cells are shaded and are becoming resistive loads the bypass diode takes the current from the lower module to the module above. The rows that are not shaded then begin to supply a current to the shaded rows. Blocking diodes are then used to ensure all modules are supplying only. This will bring the overall efficiency of the photovoltaic panel up [23].
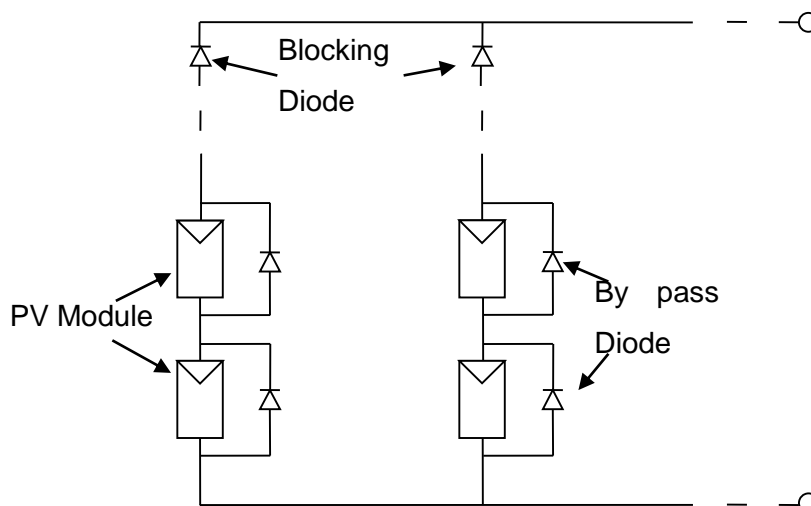
Figure 2:15: Diagram of how solar modules are connected along with bypass diodes and blocking diodes

2.16 Partial shading

The output power coming from the photovoltaic panel can have multiple peaks; even if a credit card sized area is shaded of the photovoltaic it is able to produce multiple peaks. Each photovoltaic module has a bypass diode, if the module is not generating enough power, the power from the other modules can go through the bypass diode. This will deliver the power from the rest of the photovoltaic modules to the output.

| (A) | (B) | (C) | (D) |
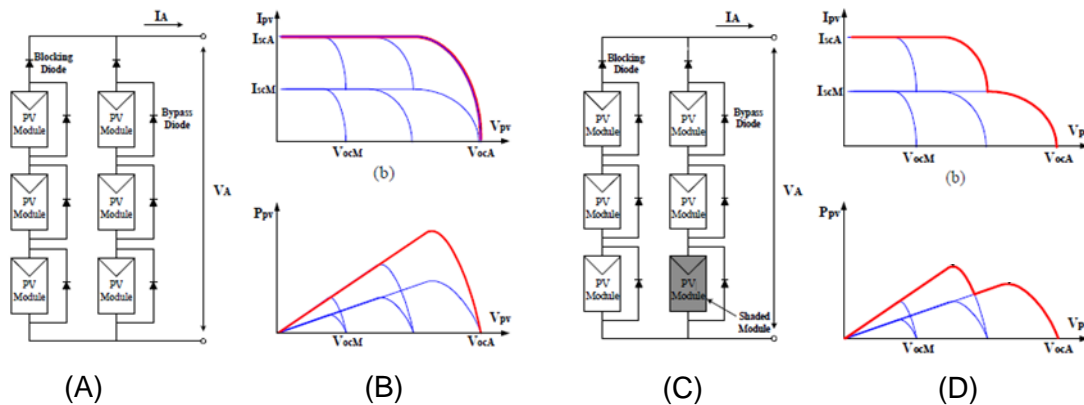
Figure 2:16: (A) PV modules and bypass diodes, (B) the I-V and P-V characteristics, (C) one module partially shaded, (D) the effects on I-V and P-V characteristics [42].

Lo   no shading. In circuit (C) one of the photovoltaic modules is shaded, the effects of this shown on graph (D). As it can be seen there is now two peaks of power. If there is a module that is inactive the entire columns voltage will be low.

2.17 Connection types

A collection of solar cells make solar photovoltaics modules, the modules can be connected in different ways to make photovoltaic panels. In the industry there are a few techniques that are most commonly used which are called series and parallel, total cross tied, honey comb and bridge linked [25] [26].

2.17.1 Simple parallel and simple series

This type of connection is where all the modules are connected in parallel Figure 2:17 (a). This means the voltage will stay the same in terms of the module output and the panel output; however the current will be added. This helps when there is partial shading due to modules that do not contribute current to the panel output, as a result they do not become a resistive load. Furthermore each solar module only requires a blocking diode; therefore a bypass diode is not required.

Simple series means all the solar modules are connected in series Figure 2:17 (b). The voltage is added and the current stays the same in this type of connection; the voltage is high and the current is low. If there is a module that is shaded a bypass diode is required to maximise the efficiency.
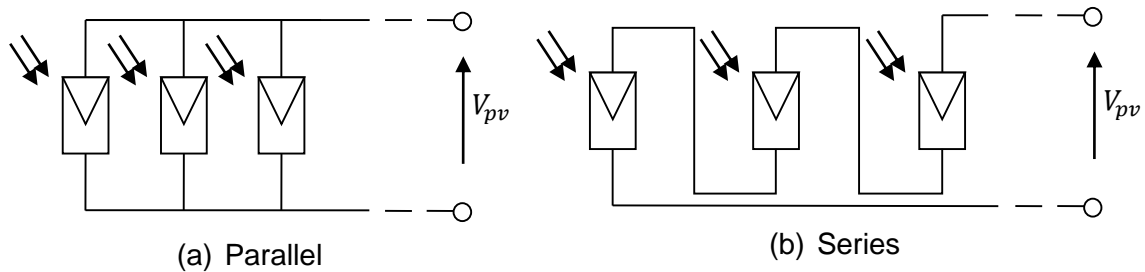
(a) Parallel (b) Series

Figure 2:17: Solar modules connected in (a) Simple Parallel (b) Simple Series

A combination of series and parallel is the most common type of connection used. This consists of a column of solar modules connected in series and a few columns connected in parallel Figure 2:15. This increases the voltage and the current.

2.17.2   Honeycomb

The Honey comb connections are linked in a special manner to form a honey comb like structure. The middle layers are in parallel and the top layer in series. The layers in between the hexagons are in parallel as shown in Figure 2:18.
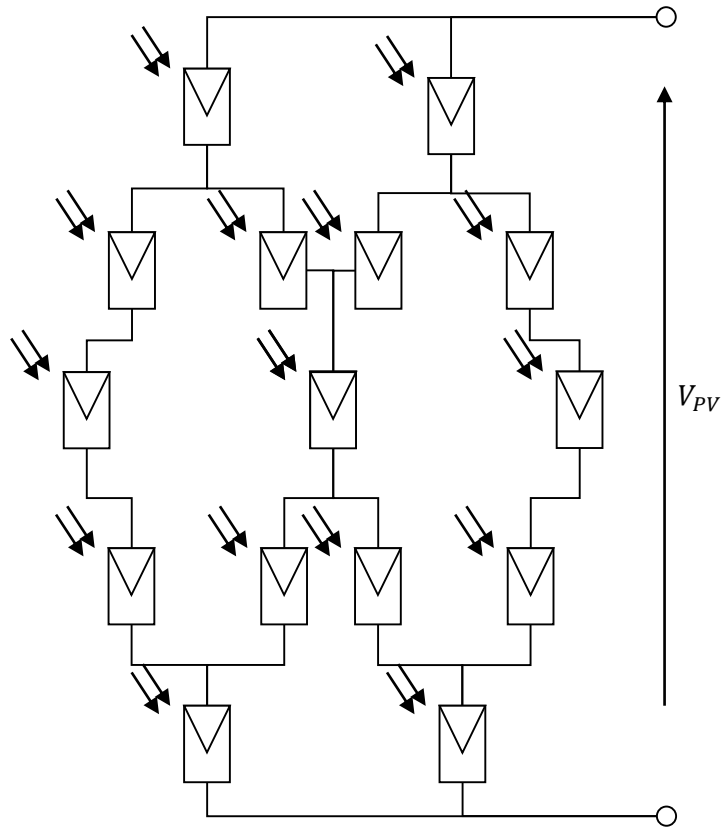
Figure 2:18: Honeycomb module connection

2.17.3 Total cross tied

Total cross tied connection is similar to parallel and series however the rows are also connected together just like Figure 2:19. This technique is effective; if one module is shaded the power goes through the other modules. Therefore in this system there is no need for bypass diodes or blocking diodes either.
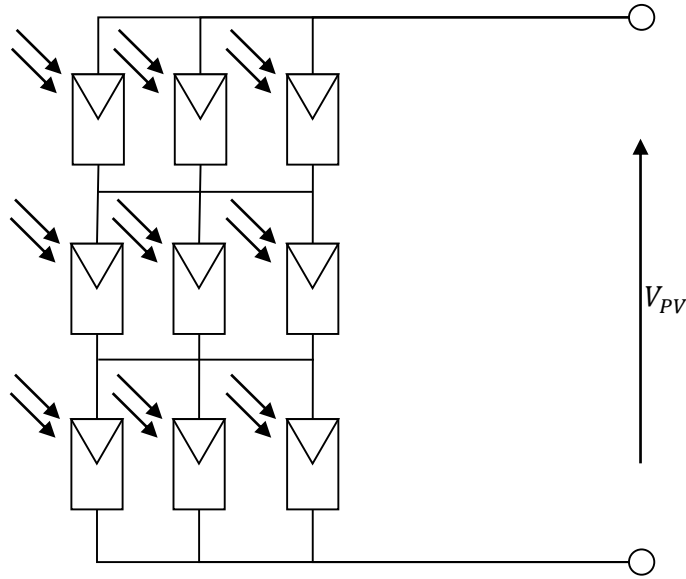
Figure 2:19: Total cross tied

2.17.4   Bridge linked

Bridge linked technique closely follows the total cross tied method. But not all rows are connected together every two modules are connected in series and the middle one is connected to the column next to it as shown in Figure 2:20. The next rows modules are then connected in the same manner but with one module short. So in essence the current finds another path if any of the modules is shaded.
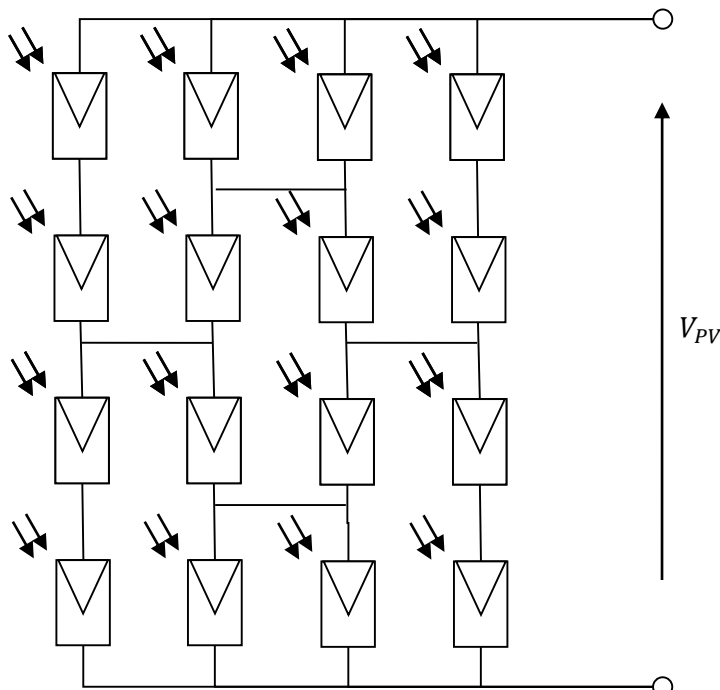
Figure 2:20: Bridge linked Connection

2.18 Voltage control

The voltage coming from the photovoltaic is a DC voltage. There are many ways to control the voltage with very little loss of power. A more commonly used method is the DC to DC converter [27].

2.18.1 Buck converter

The Buck converter steps down the input voltage by means of charging an inductor. A switch is used to decrease and increase the voltage across the inductor.
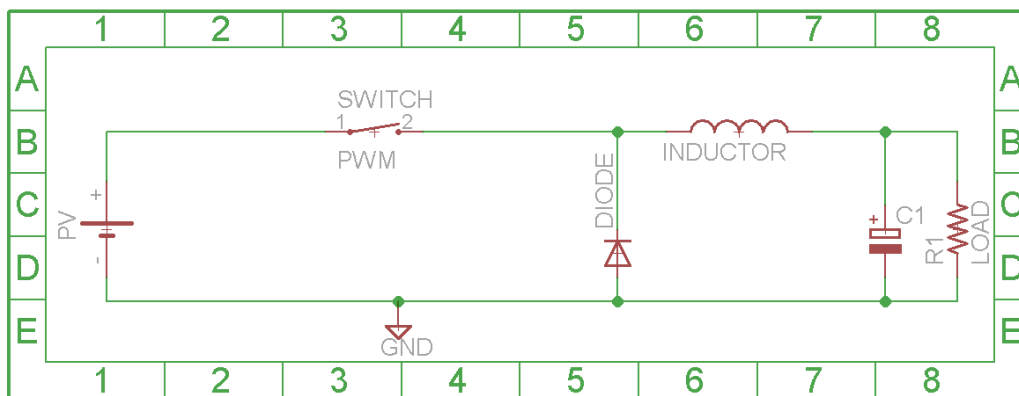
Figure 2:21: DC-DC buck converter

Figure 2:21 the switch will open and close at a frequency of approximately 10 KHz. If the frequency is too high the desired voltage will be obtained but at a cost of more power consumed for a higher frequency. However if the switching frequency is too low the desired frequency will take a lot longer to obtain. When the switch is open the circuit will drop the voltage across the inductor, and when it is closed the circuit voltage will rise. To adjust the voltage the frequency stays the same but the duty cycles of the square wave changes. The higher the duty cycle the higher the voltage, limited to the PV voltage. Also the voltage will not go lower than ground. The capacitor is used to reduce the ripple on the output voltage. The larger the capacitor the less the ripple on the output, however if the capacitor is too high the voltage may not drop.

The equation used to calculate the output voltage is:

$$Vout = D.Vin$$

Eq (3.11)

2.18.2 Boost converter

41

This circuit will step up the voltage above the PV voltage; this is achieved by opening and closing a switch rapidly to help charge the inductor to boost the voltage on the load.
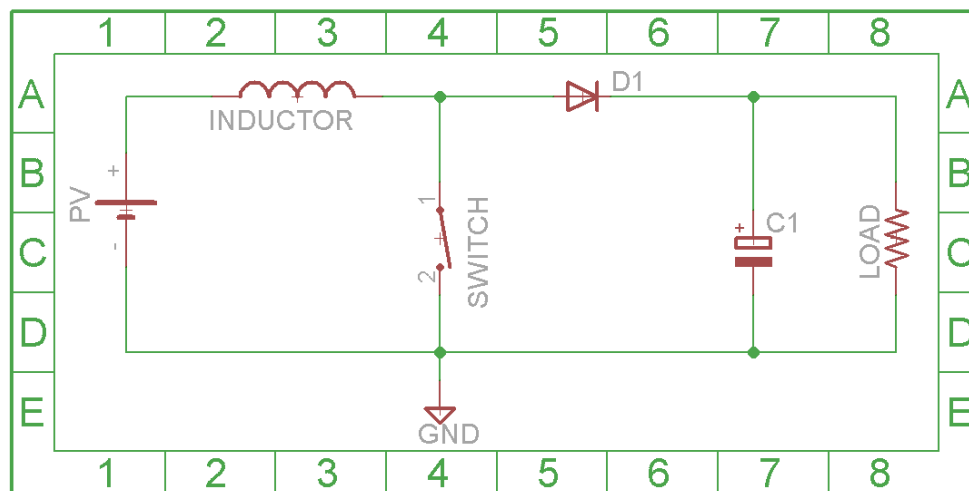
Figure 2:22: DC-DC boost converter

When the switch is closed the current goes through the inductor straight to ground; when the switch is re-opened the inductors charge goes to the load therefore increasing the voltage. Hence the switch has a frequency of approximately 10 kHz, if the frequency is too low there would a loss of power during the off stage. If the frequency is too high the inductor would not respond to charge in the current in the coil. The equation to determine the voltage is:

$$Vout = \frac{D.Vin}{1 - Duty\ cycle}$$

Eq (3.12)

2.19 Input power

The input power for a photovoltaic is the amount of light hitting the surface of the photovoltaic. This is measured in solar irradiance and the unit given is Watts per area commonly over $1\ \mathrm{m}^2$. The light is measured over $1\ \mathrm{m}^2$ however the photovoltaic panel's area is not $1\ \mathrm{m}^2$, therefore the area of the photovoltaic is multiplied by the irradiance, as demonstrated in the formula below:

$$Input\ Power = Area\ of\ PV\ (m^2) \cdot Irradiance\ \left(\frac{W}{m^2}\right)\ [23]$$

Eq (2.1)

Solar irradiance is the light coming from the sun. It varies and is never constant, since the suns position is always moving and the weather conditions are always changing. If a cloud blocks the sun's rays the light filtering through the cloud will be limited. The solar irradiance

can vary from 1360 to 0 W/m^2, zero being no light and 1360 full light in the middle of a desert [23].

2.20 Efficiency- different ways of obtaining the efficiency

The solar cell works in a way to provide current. When the load is increased the voltage will increase to a point where the current will drop out but the voltage will remain present.

2.21 Resistive load

To find the maximum power point a decade resistor can be used. As the resistance increases the voltage increases, but for the high resistance the current drops. This presents us with the IV curve. Figure 2:23 shows how the circuit is connected.
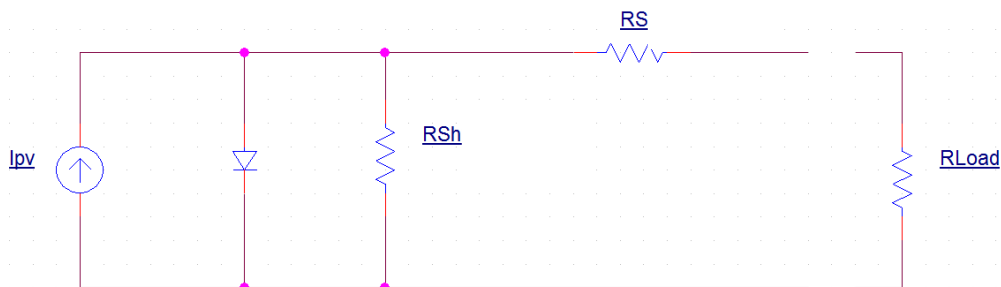
Figure 2:23: Solar cell with a variable load

When the resistance is turned up the voltage and current are measured to plot the IV curve. This helps obtain the efficiency. Table 2 demonstrates how the voltage has increased with the resistance increasing. The power is then calculated by ohms law .

Table 2: IV characteristics for a 1W solar panel

Resistance (Ω)	Voltage (V)	Current (mA)	Power (W)
Short Circuit	0	89	0
100	8.89	86	0.76454
200	10.57	85.6	0.904792
300	11	82.7	0.9097
400	11.24	78.7	0.884588
500	11.41	74.7	0.852327
600	11.55	70.9	0.818895
700	11.65	67.5	0.786375
800	11.72	64	0.75008
900	11.84	58.5	0.69264
1000	12.005	47.7	0.572639
1500	12.37	20.7	0.256059

2000	12.395	3	0.037185
2100	12.49	2	0.02498
Open Circuit	12.51	0	0

Looking at the results on Table 2, the maximum power is achieved at 300 Ω. The voltage at this point is 11 V and the current is 82.7 mA giving a power of 0.9097 W. All diodes in the system are switched on after this point and the current starts to drop. But the voltage is still present. If the readings from Table 2 were to be plotted on a graph, the graph would look like Figure 2:24.
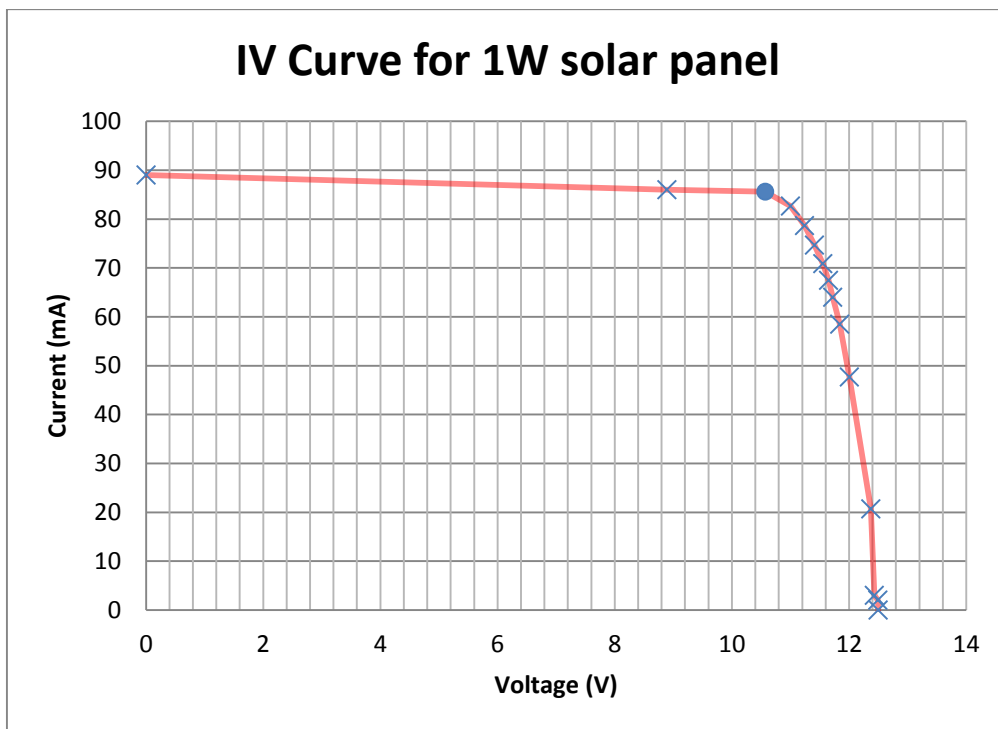
Figure 2:24: IV curve (Red line). The crosses represent the reading from Table 1. The dot is the maximum power point.

As it can be seen from Figure 2:24 the output is in a form of electrical and can be measured, but the input is in irradiance times the area of the solar cell. Irradiance is the amount of light coming from the sun. Therefore the equation is then written as:

$$\eta = \frac{Maximum\ Power}{Area\ of\ PV\ (m^2) \cdot Irradiance\ \left(\frac{W}{m^2}\right)}$$

This method of obtaining the maximum power is only for having a dc load of 300 Ω, which is not always the case. Most applications will require an AC supply. So this method is only useful for DC appliances [23].

2.22 DC to DC Conversion

Another method used to obtain optimum power is the use of a DC to DC converter. This would result in a varying current with a constant voltage output. This can then be fed into a DC to AC converter. A DC to DC converter operates via a micro controller. The micro controller will look at the current and voltage coming out from the photovoltaic and adjust the duty cycle to obtain the maximum power point.

2.23 Cell efficiency

Efficiency is the most important in everything, the less the efficiency the more energy lost. This section is focusing on the materials of the solar cell. The materials have the most important role to play in the process of exchanging energy (Solar to electrical). As observed in Figure 2:25, the solar cell efficiency research began in the 1970's and by 2015 a lot more research has gone into the cell structure, internally with the materials as well as externally with the concentrated solar cell.
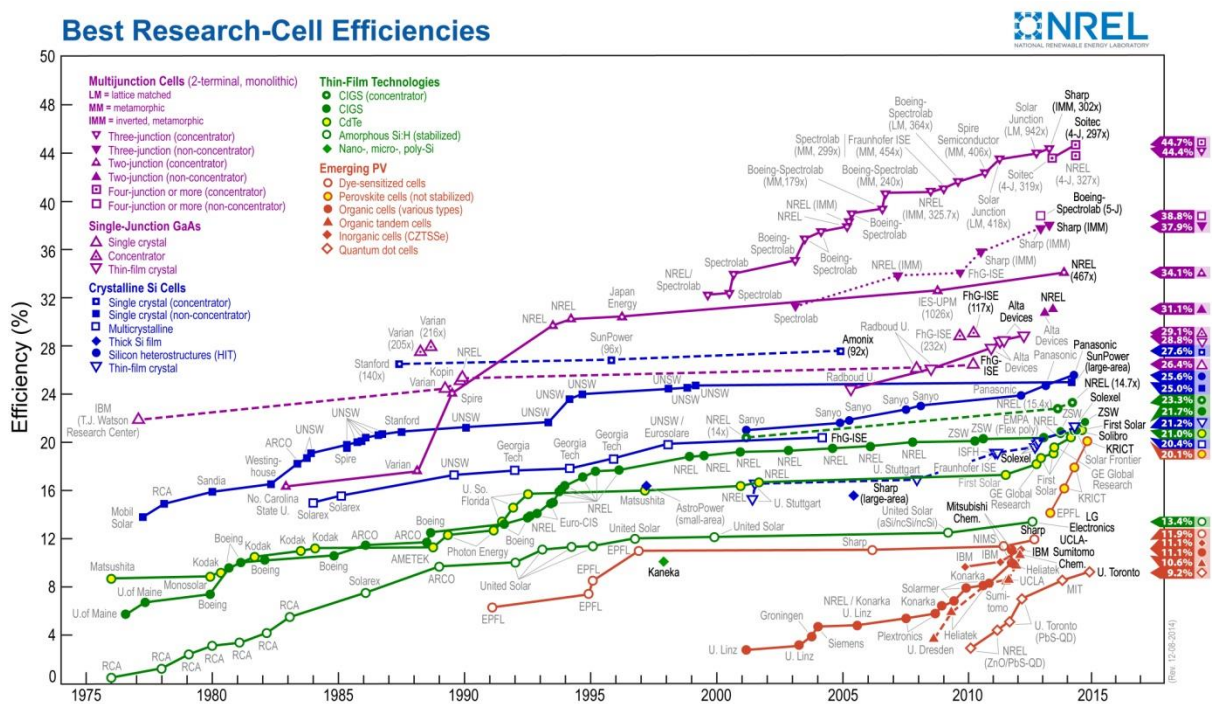
The graph on Figure 2:25 (top left corner) shows the different materials being used; the graph also shows us the progress in efficiency of each material over the years. Research is being conducted on low efficiency panels as they are more cost effective. It is cheaper to manufacture a thin film solar cell than a three-junction metamorphic solar cell. This is why companies are trying to reduce cost and increase efficiency. An ideal target is to have an efficiency of 95 % or above, which would result in very little loss of power, and to have the cost as low as possible.

2.24 The suns trajectory

The sun rises from the east and sets in the west. Its position in accordance to the earth is never constant. The sun shines from the north or the south upon countries close to the equator line depending on the season. It shines from a southern direction on countries in the northern hemisphere and from a northern direction on countries in the southern hemisphere. The angle of the sun moves by 47º this is because the earth orbits the sun at a tilt of 23.5º. Figure 2:26 shows where the sun rises in the summer (yellow) and winter (Red). The orange line is the suns position and takes place twice a year, once in spring and once in autumn. The numbers on the lines indicate the time of the day. For summer the sun rises at approximately 3.00 am. And in the winter the sun rises at approximately 8:00 am [29].
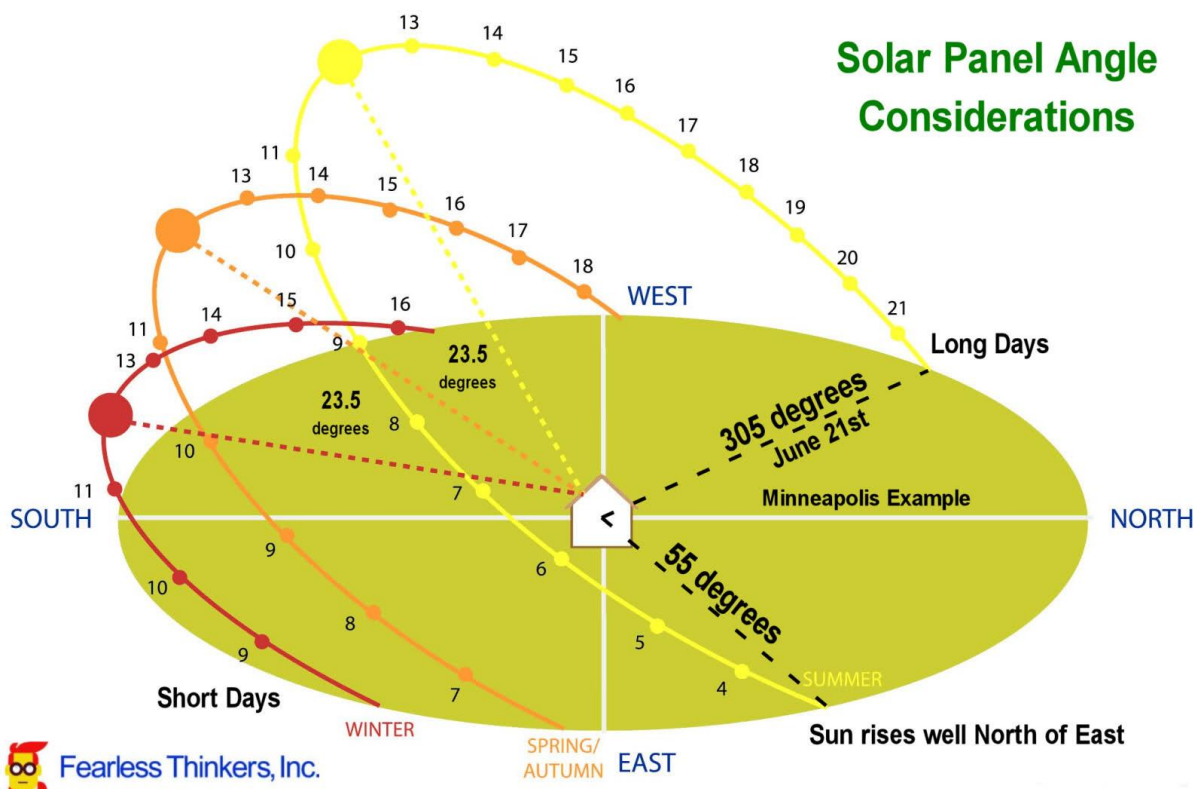
Photovoltaics' are installed on roof tops or in solar farms are fixed at a 45º angle facing south. Although this captivates a lot of the suns power it also loses out on potential power. On the longest day in summer a fixed photovoltaic is losing approximately 7 hours of light, due to the fact that the PV was not facing the sun. The light shining directly on the panel is not always at a 90º angle which is the most effective.

2.25 Angle of light

Most photovoltaic panels are fixed on the roofs of houses or in a farm. They are fixed in a position generally facing south at a 45º tilt. The Photovoltaic is dependent of solar irradiance; the solar irradiance hitting the panel on an angle of 0º will deliver optimum power. On a fixed photovoltaic panel the light is only hitting the panel on an angle. The effect of the light on the photovoltaic panel have a corresponding effect on the output power as shown in Figure 2:27.
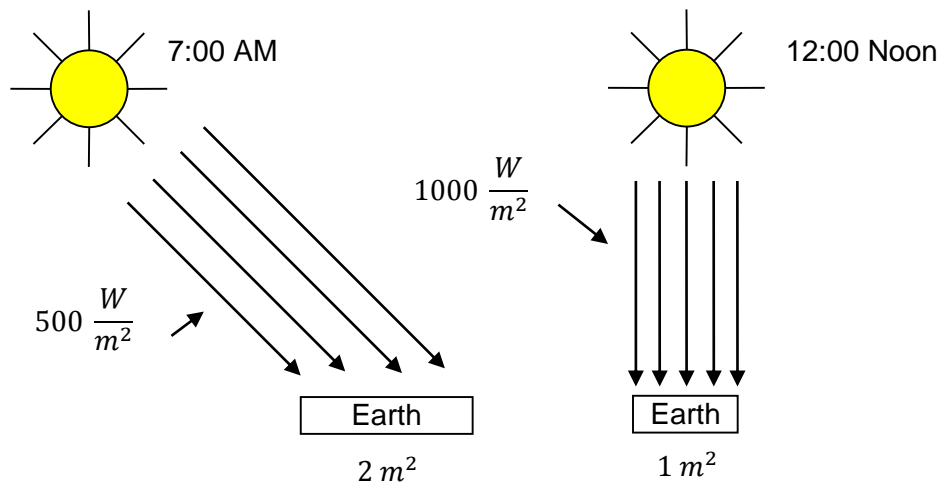
Figure 2:27: The intensity of the angle of light

The efficiency of the photovoltaic decreases by the cosine of the angle of light. The efficiency is the calculated by Eq(2.3) [23].

$$\eta * \cos(\emptyset) \rightarrow \left(\frac{\text{Power in}}{\text{Power out}} \right) * \cos(\emptyset) \qquad \text{Eq(2.3)}$$

There are currently 2.48 Giga watts of photovoltaic panels that are fixed in one direction and one angle. That is a lot of power loss when collated together.

2.26 Concentrated photovoltaic

Concentrated Photovoltaic uses concaved mirrors to concentrate the solar irradiance to a small photovoltaic. Therefore the photovoltaic gets solar irradiance from a larger area. This

amplifies the solar irradiance on the photovoltaic. The solar cells used in these systems are the three junctions photovoltaic which are capable of having an efficiency of 44.4 %. Looking at Figure 2:27, the rays work within a certain range. This is due to the reflection of the light to the solar cell. When the suns position moves the entire system moves with the sun to obtain optimum power.
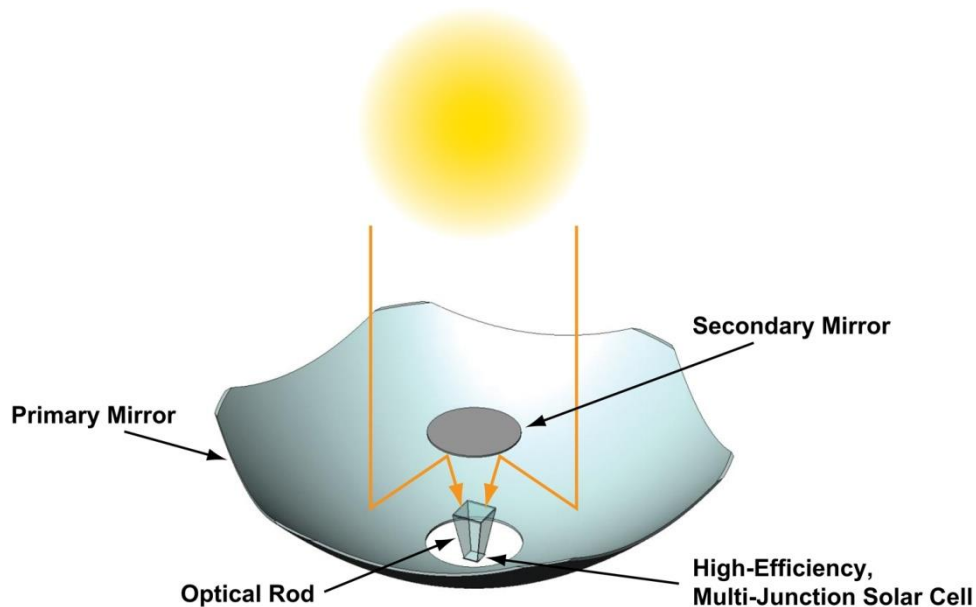
Figure 2:28: A diagram to show how the concentrated photovoltaic works [30]

Another method of concentrated photovoltaic is to follow the suns trajectory as it passes from east to west. This system requires motors to constantly move the photovoltaic panels to follow the sun. The movement of the motors are minute but constant therefore the photovoltaic reposition throughout the day. This uses energy to move the panels bringing the overall efficiency down. Two motors are used in this method, one to control the direction of the sun and the other to control the angle of the sun.

3 System modelling and simulation

3.1 Modelling

Modelling and simulating is a significant tool for any project as this will give an insight into the expected results. The simulation can be modelled according to the specification of the physical design. This would save time and money as problems that may occur can be seen before implementing a physical model. For this project the simulation can be split into a number of sections and tested individually before collating. The individual sections can be split by the following:

- Designing of a prototype test rig where concentrated photovoltaic will be developed
- Modelling a solar cell with the diode characteristics and solar irradiance to a current source
- Modelling a photovoltaic panel with capability to give a curve for partial shading
- Construct the algorithms with partial shading and a tracking algorithm
- Combine a partially shaded photovoltaic with a buck converter and the tracking algorithm

3.2 Concentrated photovoltaic

Concentrated photovoltaic is when the photovoltaic panel tracks the sun so all of the solar irradiance are hitting the photovoltaic panel proportionally and not with an angle. For this a prototype test rig is made to track the most amount of light. Some designs get the coordinates of the suns movement and track the sun according to the coordinates, whereas other designs use power readings from the photovoltaic. Both methods use energy to keep the motors tracking the sun at all times.

As shown in Figure 3:9 the efficiency of the system starts to decline after 5º. There is only a 10 % loss in power, when the light is at an angle of 25º. A phototransistor can be used to measure the light at 45º to the left and right of the panel. It will give the same readings if the light is at 0º to the panel. Higher readings on one side effectively indicate that light is at an angle to the panel therefore the panel needs to adjust in the direction of the light to make the readings similar. The panel will only need to move from east to west due south and from 12º longitude (in winter) to 60º longitude (in summer) for Manchester. To achieve this two motors will be used, one for the direction and the another for angle. Therefore four phototransistors will be used; two for the direction and two for angle. Figure 3:1 is showing the model design,

which is not to scale, also how the phototransistors will be placed and the direction they will be pointing. The arrows indicate the direction that the sensors will measure the light.
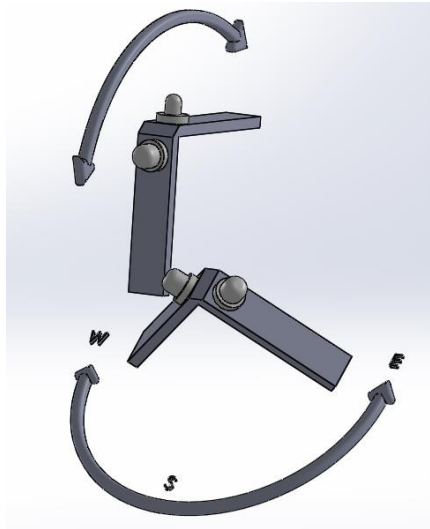
Figure 3:1: A model diagram of how the phototransistors will be placed

As the photovoltaic panels used are small the prototype test rig can also be small. The design for the test rig can also be made larger for larger panels. Figure 3:2 illustrates the prototype test rig designed in solid works. The movement of the test rig is illustrated by the arrows on the design in Figure 3:2. The black box at the base of the rig is the motor that will move the rig from east to west. The black box shown on the back of the rig is the motor that will move the panels vertically. The rig sits on the shaft of the motor that is at the base, for a small test rig this is sufficient. For a larger model a thrust bearing can be used to carry the weight or a thicker shaft.
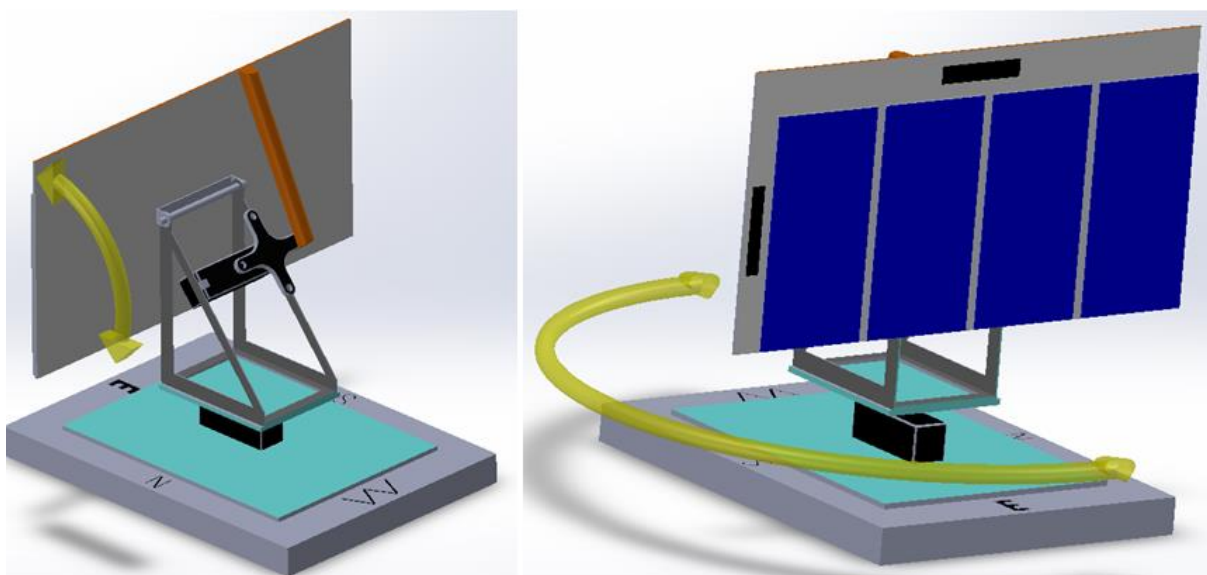
Figure 3:2: The prototype test rig

On the face of the test rig there is 2 black rectangles one above the panels and one beside the panels. This space is where the phototransistors shown in Figure 3:1 will sit. The sensor above the panels will determine the direction of the light and the sensor beside the panels will determine the angle of the light. Servo motors are used in this design that require a pulse every 20 milliseconds. The length of the pulse is what determines the position of the motor. These motors where specifically chosen because there total movement is 180^0 . Figure 3:3 is the flow associated with the movement of the rig according to the phototransistors.
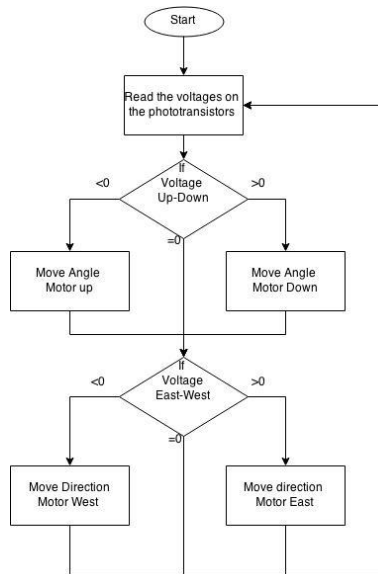
Figure 3:3: Flow code of how the sensors will move the motors

As the flow code explains, for each sensor, there are 3 possible outcomes. Firstly if the subtracted voltages are positive the motor needs to move the panels' direction down or east. Then if the subtracted voltages are negative, the motors need to move the panels' direction up or west. Finally if there no difference between the voltages there would be no need to move the panels. This program will also be part of the power tracking algorithm as this program does not required to be running continuously.

3.3 Modelling of a solar cell

3.3.1 Diode
The solar cell can be divided into two parts; the first part involves modelling the diode as it is a crucial part of the solar cell. The diode current can be expressed as:

$$I_D = I_S \left(e^{\frac{qV}{nkt}} - 1 \right) \tag{5.1}$$

In the above equation the variables that affect the output is the temperature and the voltage across the diode, the rest of the elements are constants. Therefore looking at Figure 3:4 the

inputs are temperature (Tc) and voltage (V). Each mathematical block is representing part of the diode equation and below each box the part the equation that the system is computing is inscribed.

I_s= Dark saturation current

V= Voltage across terminal of diode

q= electron charge

k= Boltzmann's constant

n= Ideality factor

t= Temperature
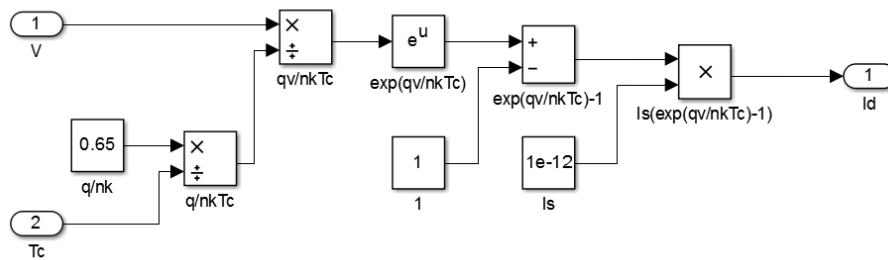
Figure 3:4: A Simulink model for a diode

To illustrate the effects of temperature on a diode, the testing temperature applied to the model in Figure 3:4 (port Tc) will be 20°C, 25°C and 30°C. This will show that the cooler the temperature the higher the switching on voltage of the diode as shown in the graph of Figure 3:5. The voltage applied to the model in Figure 3:4 is like having a power supply. The voltage is increased from 0 to 1 over 1 second to give the exponential curves in Figure 3:5.
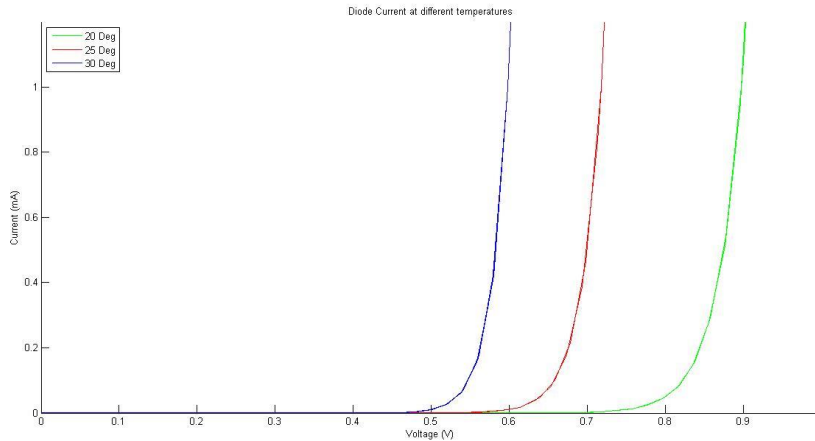
Figure 3:5: A graph for the diode current

Now that the diode is functioning with different temperatures, this module can be added into a solar cell.

3.3.2 Solar cell

In a solar cell there is a diode and a constant current source. Figure 3:6 shows how the diode and the current source are placed together. When the diode switches on, all the current that the current source (I_{ph}) produces goes through the diode. Before the diode switches on the current is constant.
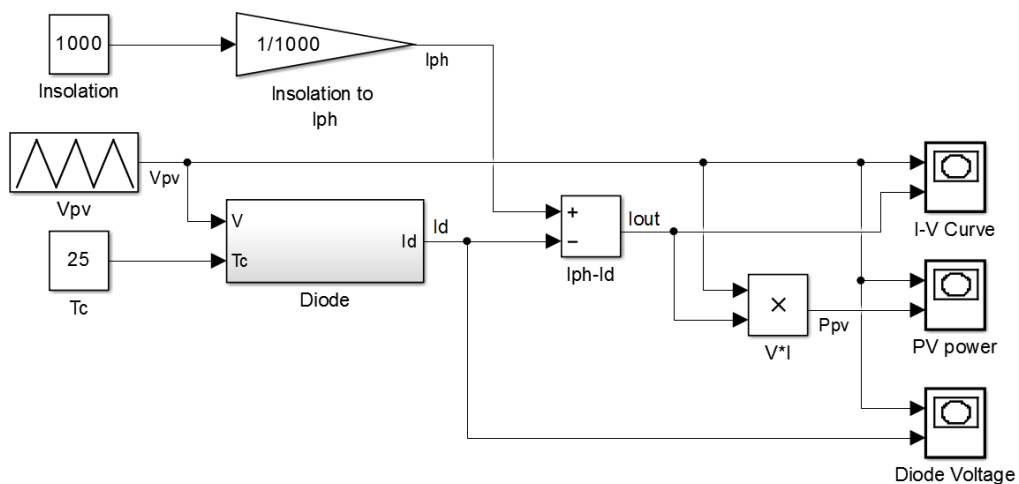
Figure 3:6: A Simulink model of a solar cell

Once the diode is switched on, the current flows through it resulting in an exponential curve to V_{oc}. Figure 3:7 demonstrates how the diode switches on and takes all the current off the solar cell.

53

The IV curve of a solar cell with Different intensities of light
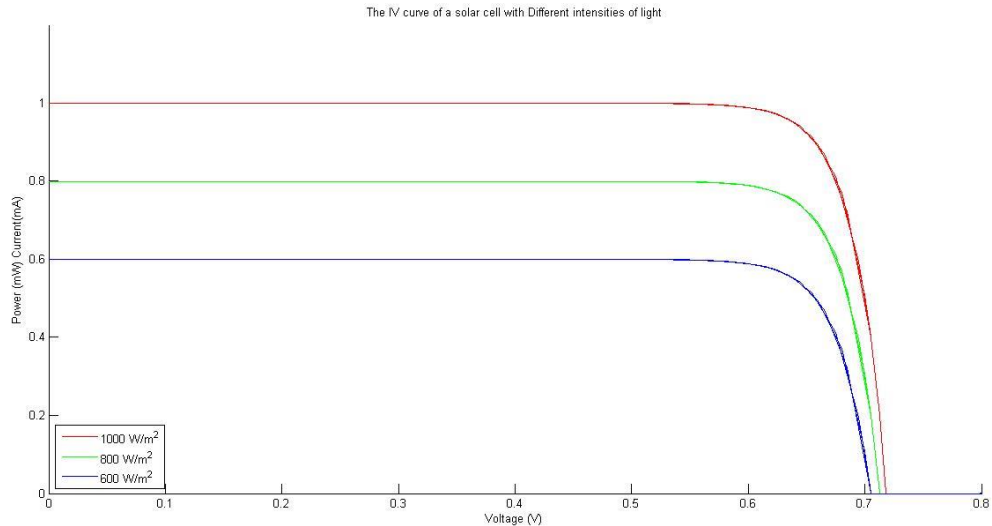
Figure 3:7: A graph showing the IV curve at different irradiance

This model is an example for a single solar cell, for multiple solar cells in parallel the diode switch on voltage is higher and the irradiance is multiplied.

3.3.3 Angle of light

The angle of which the solar irradiance hits the surface of a photovoltaic cell affects the total performance of the solar cell. The sun is not always at a fixed angle in a fixed direction whereas the photovoltaic is fixed. Generally if the photovoltaic panels were to be fixed, they would be facing south and at an optimum angle, so when the sun is at its peak it would be at 0° to the photovoltaic. This only occurs once a day at noon. The rest of the time the suns irradiance is not at 0° to the photovoltaic. This brings the efficiency of the photovoltaic down.

The solar irradiance is measured in watts per 1 meter squared. When the angle of light is included into the equation, the total current is multiplied by the cosine of the angle of the sun. As shown in equation 5.2

$$I = \left(I_{ph} - I_d\right) \cdot \cos \emptyset \tag{5.2}$$

Figure 3:8 shows how the solar cell model from Figure 3:6 is configured to include the angle of light. The graph also shows the performance with the angle of the sun. Assuming the solar irradiance does not change at all; at 0^0 the current will be normal just as in Figure 3:7, however since the angle of the light increases the efficiency of the solar cell decreases.
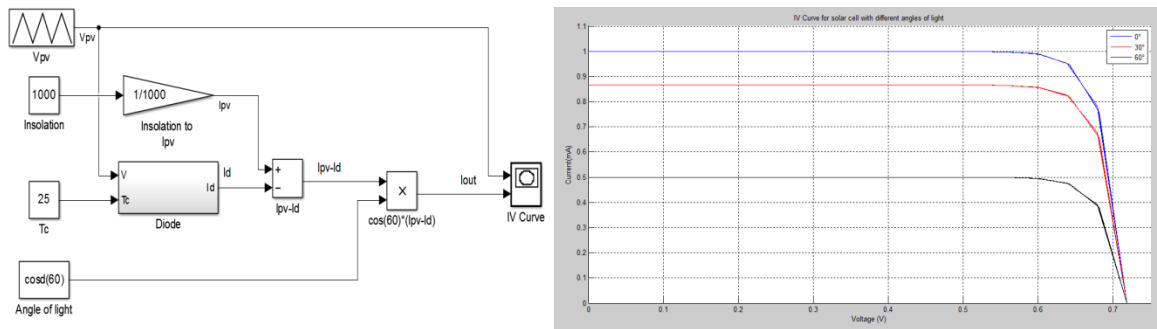
Figure 3:8: A Simulink model and graph for the angle of light

The current will decrease by the cosine of the angle of which the irradiance is hitting the solar cell. When the lights angle gets to 60° the efficiency is halved, this is because $\cos(60) = 0.5$. Figure 3:9 presents how the angle of light will decrease the output power.
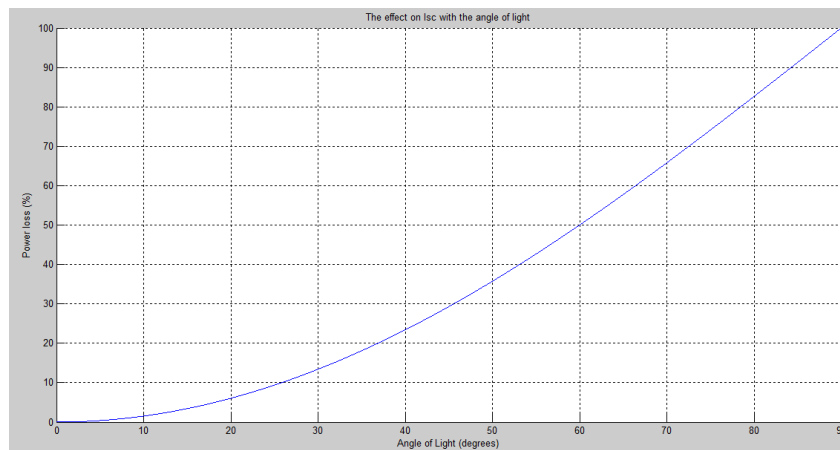
Figure 3:9: The percentage of power lost due to the angle of light

3.4 Photovoltaic panel

The photovoltaic panel model is similar to the solar cell module because a panel is made of many solar cells connected in series and parallel. Each photovoltaic modules have different characteristics. They are outlined in Table 3. But with one module the effects of partial shading cannot be tested. Therefore four panels will be used, two in rows and two in columns.

Mono-Crystalline Silicon	Conditions	Typical Value	Units
Maximum Power	1,000 W/m² , 25°C	1	W
Maximum Power Voltage		6	V

Maximum Power Current		170	mA
Open Circuit Voltage		6.9	V
Short Circuit Current		180	mA
Number of Cells		12	
Size (L, W,D)		125*63*3	mm

Table 3: photovoltaic module characteristics

One method of simulating the photovoltaic panel, in Simulink is to create a Matlab function file. Which will handle all the parameters and equations. The equations are the exact same as the solar cell but for more cells. In the program the information from the data sheet will need to be entered.
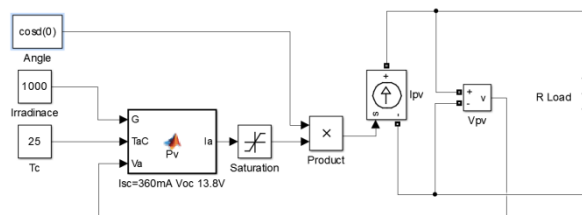
Figure 3:10: Model of a photovoltaic using Matlab function file

Looking at Figure 3:10 the RLoad can be a resistive load or a DC to DC converter to optimize the maximum power. The results are sown in Figure 3:11, as the voltage increases the current exponentially drops to V_{oc}.
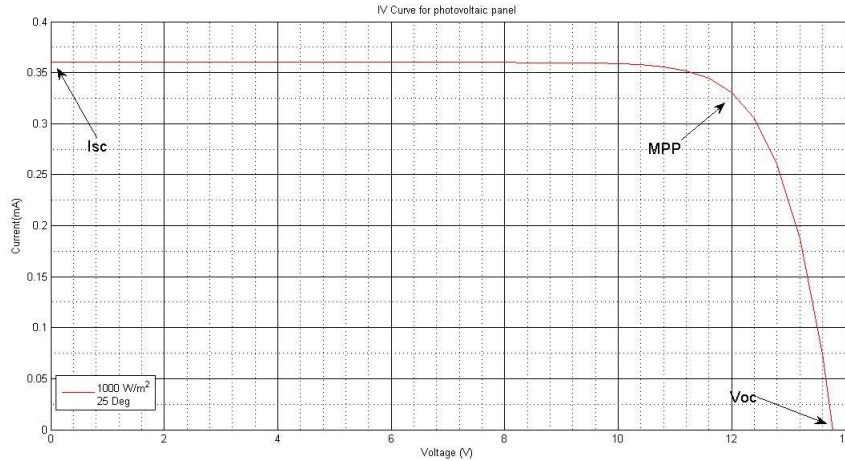
Figure 3:11: A graph showing the IV curve for Figure 3:10

3.4.1 Partial shading

In partial shading the number of power peaks is given by how many columns of photovoltaic modules it contains. For example if there are two columns of photovoltaic modules the output could only have maximum of two peaks of power. The algorithms will have to be modified to find the maximum power point. The only way to find out if the peak is global or local is to change the duty cycle and measure the power. This is because the irradiance can change and the global peak can become the local peak. Figure 3:12 shows how the global peak can become a local peak. In both cases one of the modules is shaded completely; this could be because of dirt covering the entire module. Initially the total irradiance on the panel is $250 \frac{W}{m^2}$, this could be because of a cloud passing by. After a duration of time the irradiance increases and the output will show a higher peak at a lower voltage.
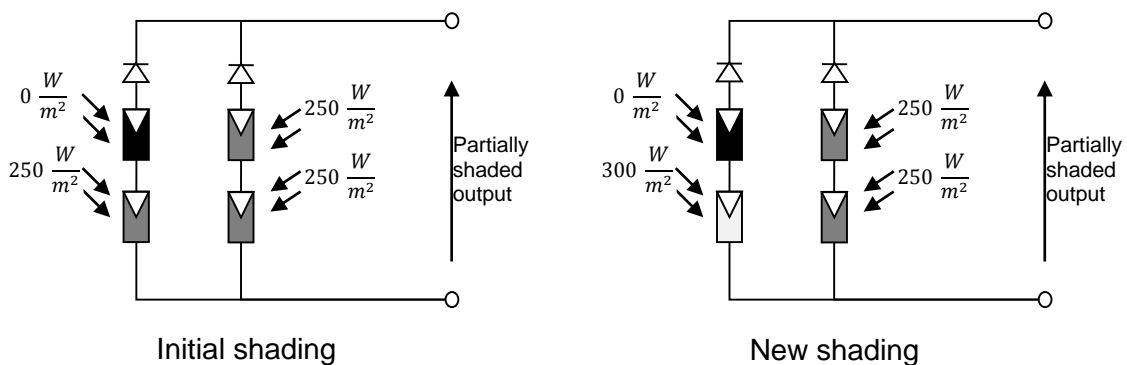
Figure 3:12: Shading effects on photovoltaic modules
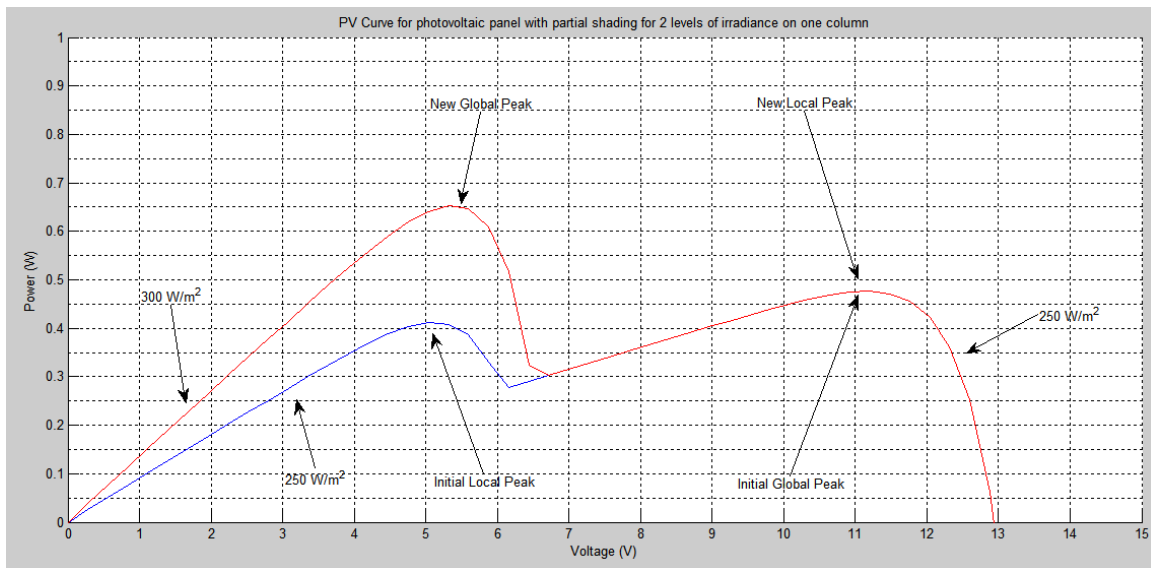
Figure 3:13: A graph showing the effects of different levels of shading on the PV curve

Figure 3:13 shows how the global peak can become the local peak because of the amount irradiance changing. The graph has been simulated using the parameters from Figure 3:12. This transition is not dependant on time due to the causes of shading are completely random.

Perturb and observe algorithm measures the power and determines the direction of maximum power point. For a generic algorithm that will fit all systems regardless of how much power is available, the algorithm will need to scan from I_{sc} to V_{oc}, and then determine the maximum power point. Another way of looking at the problem is to find where the peaks can be and fit the algorithm to track within that region.

3.5 Algorithms

A tracking algorithm can be used to find the maximum power point. Although there are several algorithms used in the industry; algorithms more commonly used are perturb and observe and incremental conductance. There are also several ways to simulate the algorithms within Matlab and Simulink. These algorithms find the first peak of power, to find all peaks the algorithms will be modified to find the global power peak.

When partial shading occurs there is more than one peak of power. The modified algorithm must extend its search from virtually the minimum voltage to the maximum voltage. This can be applied to both algorithms identically. The program will log the voltage with the corresponding power, it then increases the voltage from minimum to maximum taking all readings as it increases the voltage. With the information logged the global peak can be detected. Second step would be to go close to the voltage at the global peak to let the

58

algorithm take over and track the optimum power. After a certain amount of time the system will need to scan again and repeat the process. Figure 3:14 illustrates a flow chart of how the programs are modified to find the global power peak.

Initially the program will send the voltage close to V_{oc} which is 13.8 V, but as there physically can't be peak of power higher than 12 V the algorithm doesn't need to go to absolute V_{oc}. The same analogy could be made for when the algorithm is decreasing the voltage in the last step. The middle steps are to track the global peak with perturb and observe algorithm or incremental conductance for a given amount of time. Moreover the algorithms increase or decrease the duty cycle by 0.5 %, but the scanning process does not require a small step size in the duty cycle, it can be varied by 10 %.
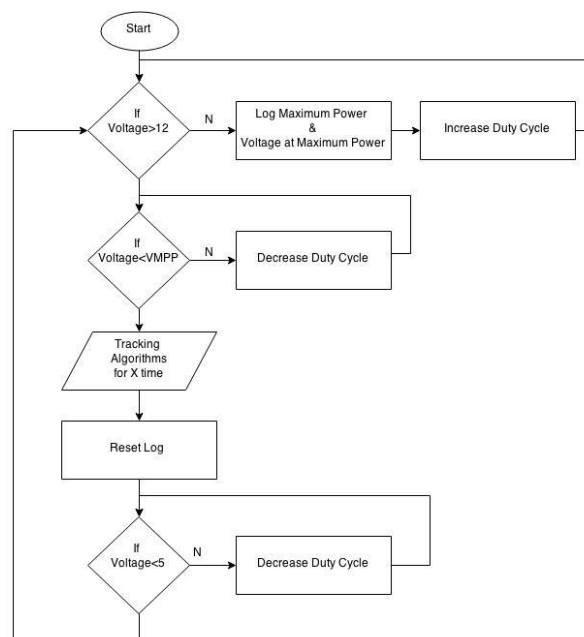
Figure 3:14: A flow chart showing how the modified algorithm will operate

When simulating this in Simulink it is simpler to understand that each step runs at one time. Therefore the first step would be to increase the voltage to 12 V, once reached 12 V the algorithm can go to the next step. In Simulink this process would require a control signal which would control which step to execute. The actual algorithm will be controlling the duty cycle Table 4 shows how the algorithm will scan the entire power curve to keep track of the global peak.

Step number	Control	Algorithm	Description
Step: 0	`if (Voltage>12)`	`if(Voltage<12)`	Increase

59

	Step=1; else Step=0; end	Duty=Duty+0.1; else Duty=Duty-0.1; End	voltage until it reaches 12 V

Step: 1	If (Voltage==VMPP)
	
	    Step=2;
	
	else
	
	    Step=1;
	
	end
		if(Voltage<VMPP)
		
		Duty=Duty+0.1;
		
		else
		
		Duty=Duty-0.1;
		
		end
			Go to the Voltage where the global peak is

Step: 2	if (Time==1)
	
	    Step=3;
	
	else
	
	    Step=2;
	
	end
		if(Power<P_power)
		
		Duty=Duty+0.005;
		
		else
		
		Duty=Duty-0.005;
		
		end
			Stay at the tracking algorithm until a certain time

Step: 3	if(Time==0)
	
	    Step=4;
	
	else
	
	    Step=3;
	
	end
		MPP=0;
		
		VMPP=0;
			Reset the maximum power values to scan again

Step: 4	if(Voltage<5)
	
	    Step=0;
	
	else
	
	    Step=4;
	
	end
		if(Voltage>5)
		
		Duty=Duty-0.1;
		
		end
			Drop voltage to 5 V to scan at a lower voltage

Table 4: A table showing the relationship of the step and the duty cycle

3.5.1 Perturb and observe

Perturb and observe algorithm adjusts the duty cycle and looks at the response of the power out of the photovoltaic. If the duty cycle is increased then the power also increases, the algorithm will keep on increasing the duty cycle until the power starts to drop.
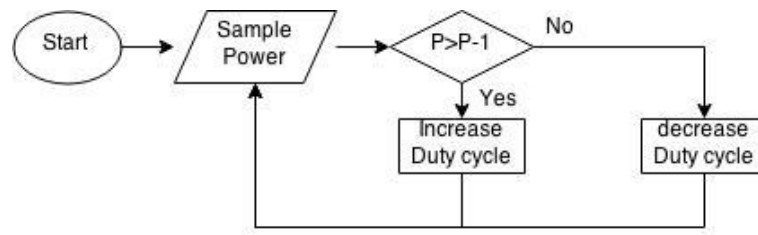
Figure 3:15: A flow chart showing perturb and observe algorithm

Figure 3:15 illustrates how the algorithm operates in a flow chart. Hence in Simulink the program must operate in the same process. The Simulink part firstly has to sample the power then it compares the current sample and the previous sample. A Matlab function file can be used to compare the previous power to the current power reading to determine the duty cycle.

Figure 3:16 highlights how the Matlab file is connected and the program that the Matlab file contains. The Matlab file runs continuously, the code does not run line by line, so there are delays induced outside the code. In a real world application the system will sample the voltage and current. Then multiply the two in software. This is why the block sample and hold is on the input power.
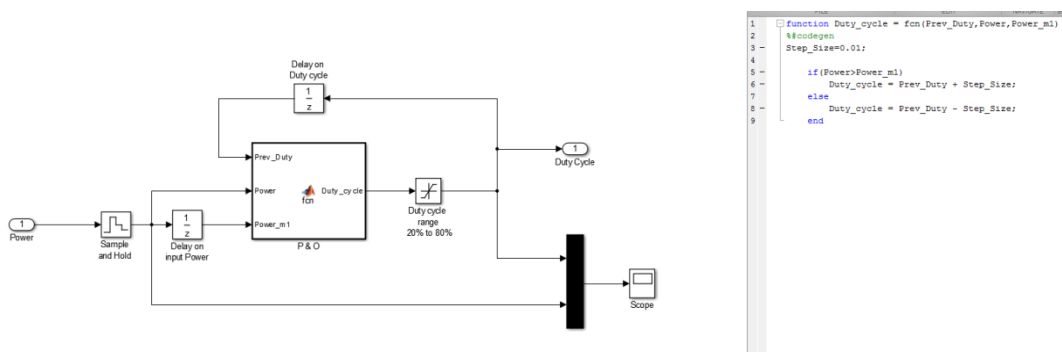
Figure 3:16: Perturb and observe algorithm using a Matlab function file

For test purposes the system only requires the power, range is not important; a simulated power can be presented via a repeated sequence. This repeated sequence is a simple triangle wave at the frequency of 50 Hz. On the incline of the triangle wave the duty cycle should increase. As soon as the power starts to drop the duty cycle will also start to drop trying to hover around the maximum power. Figure 3:17 shows how the comparator will

61

compare the two power readings; the results are shown on the graph on the right of Figure 3:17.
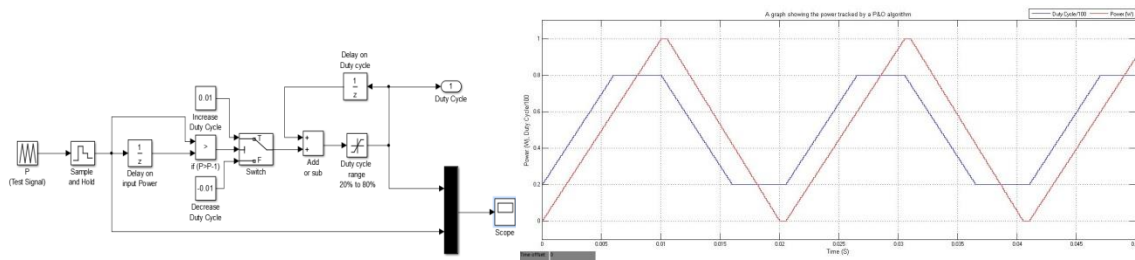
Figure 3:17: diagram: Perturb and observe algorithm using a comparator graph: Simulation result

Looking at the results of perturb and observe in Figure 3:17, as the triangle wave increases the duty cycle increases. As soon as the triangle wave starts to descend the duty cycle starts to decrease. The reason why the duty cycle saturates at 80 % and 20 % is due to the buck converters limits. The buck converter must operate within this range, anything more than 80 % or less than 20 % and the inductor will not hold the charge adequately.

3.5.2 Incremental inductance

Incremental conductance is one of the most used algorithms. It works by determining the slope of the power. If the slope has a positive gradient then the duty cycle will be increased as the maximum power is at a higher voltage. If the slope has a negative gradient then the maximum power point is on the left which is a lower voltage, so the duty cycle will be decreased.
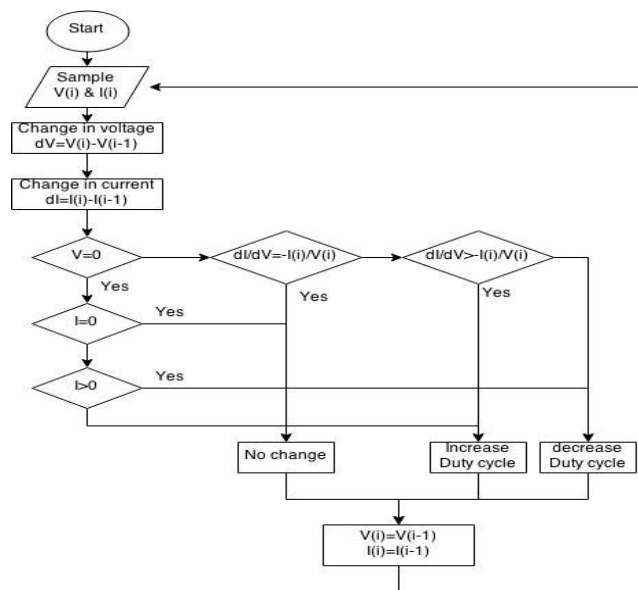
Figure 3:18: Flow chart showing how incremental conductance operates

62

Looking at Figure 3:18 the algorithm is concerned with the change in voltage and the change in current. If there is a change in voltage or current it will then determine if it is a negative change or a positive change.
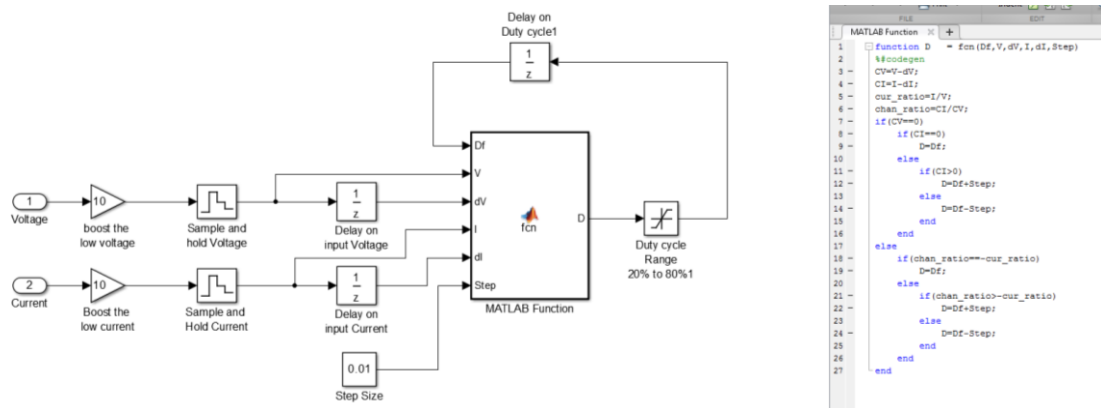
Figure 3:19: A model of the incremental conductance algorithm in Simulink

3.6 Results

A comprehensive comparison of the two algorithms will be evaluated under the same conditions. The full system contains a partially shaded photovoltaic connecting to a buck converter with a tracking algorithm. The partially shaded photovoltaic applied to the system will be similar to the one shown in Figure 3:13, where the first peak will initially be the global peak which will then become the local peak. The algorithm will be the comparison of perturb and observe versus incremental conductance, both with the generic tracking algorithm explained in chapter Algorithms.

The conditions that the systems evaluate have a total run time of 0.4 seconds. The irradiance will change at 0.15 seconds. This will show the first peak transitioning from the global peak to the local peak. The algorithm will scan to find all the peaks every 0.2 seconds, this is sufficient to demonstrate the findings in simulation, but in a real world application the algorithm can scan for all the peaks every 15 minutes.
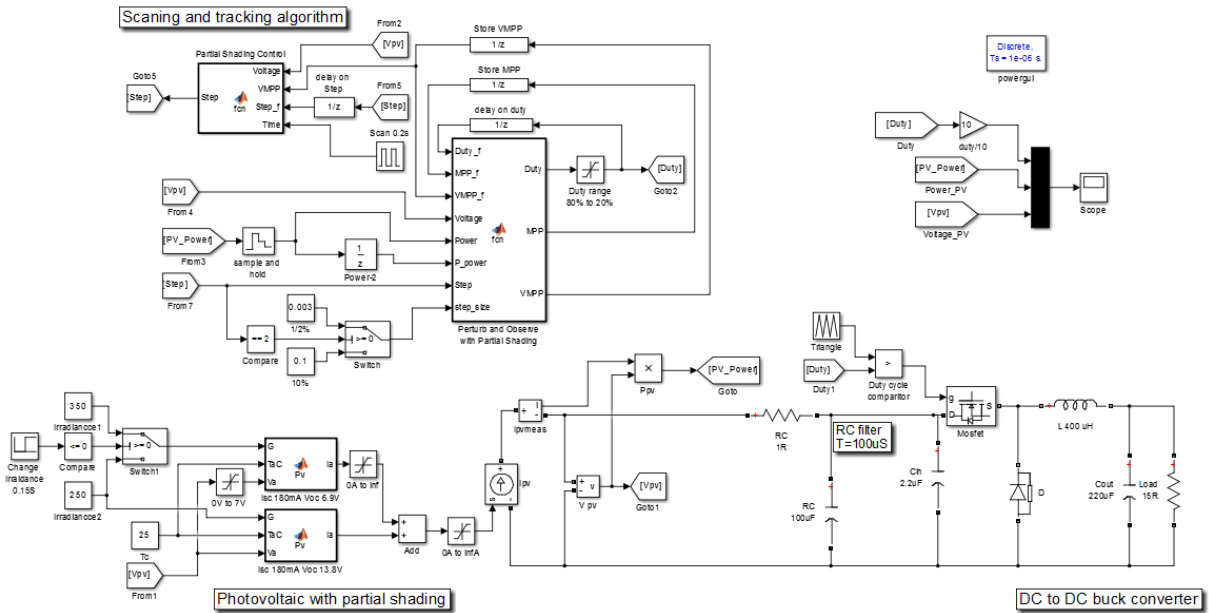
Figure 3:20: Full model system with perturb and observe algorithm and partial shading

Figure 3:20 is the full model with a partially shaded photovoltaic input to a buck converter. The control section above only looks at the power and voltage coming from the photovoltaic. In between the current source (Ipv) and the buck converter a RC filter is placed, this is to smooth the systems operations. When the MOSFET is closed in the buck converter, the current rapidly drop to zero, with the RC filter in the circuit the capacitor holds the charge but slows down the overall system response.
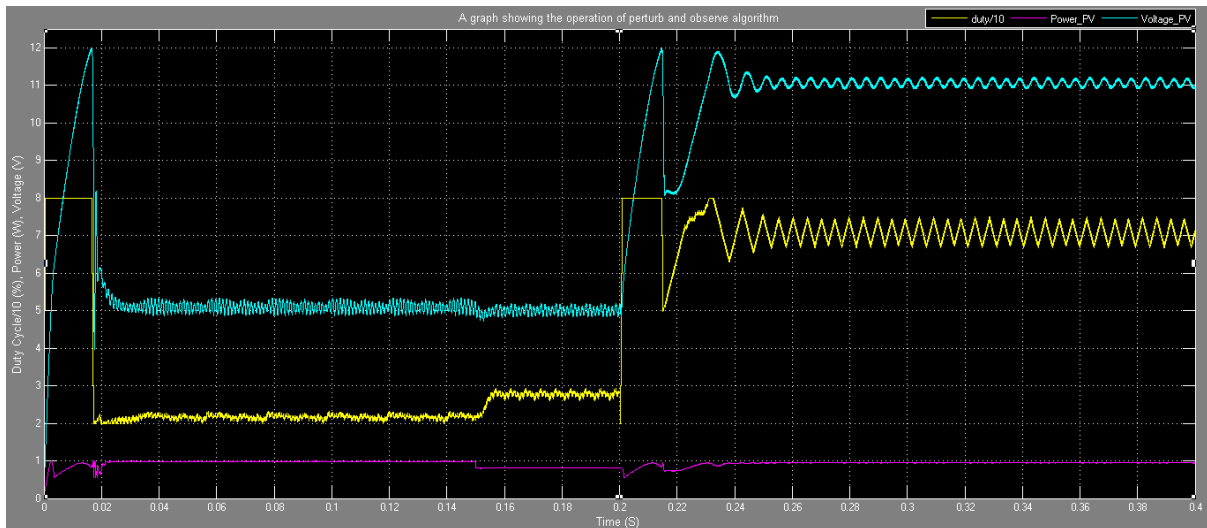
Figure 3:21: A graph showing the response of Figure 3:20

Figure 3:21 shows the simulation result for the perturb and observe algorithm model in Figure 3:20. As seen in Figure 3:21, the total run time is 0.4 seconds and the system scans for peaks at 0.2 seconds. The overall response to scan the peaks and go to the maximum power point is 22 milliseconds. At 0.15 seconds the power level changes from 1 W

($350\ W/m^2$) to $0.8\ W$ ($250\ W/m^2$) and the duty cycle (Yellow) tracks the change and observes the maximum power point. This takes 4 milliseconds to adapt to the change. Figure 3:22 is a zoomed in image of the graph in Figure 3:21, this shows data from 0 seconds to 25 milliseconds and demonstrates the process of how the system obtains maximum power.
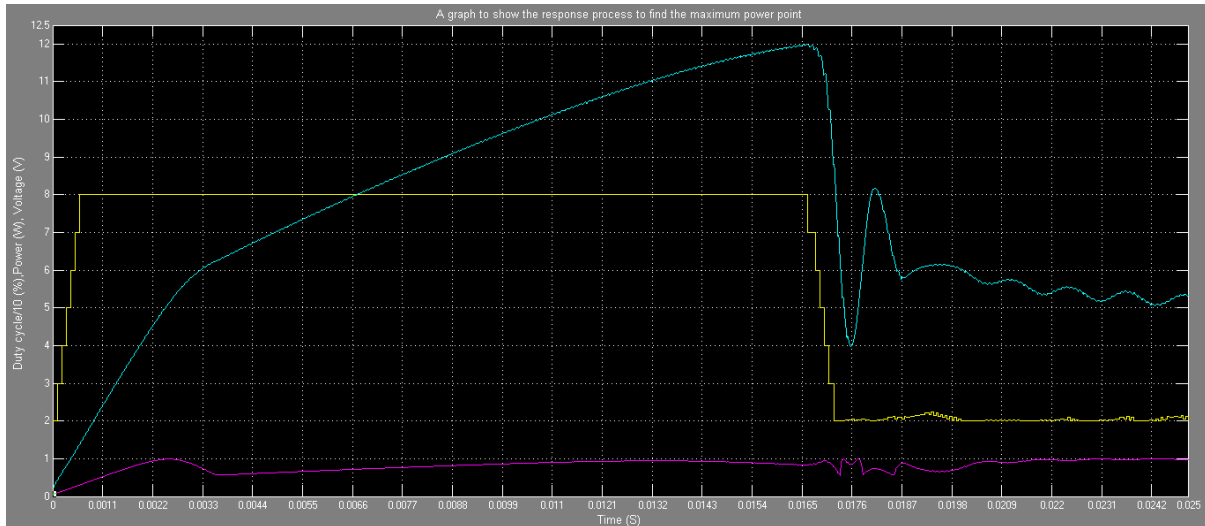
Figure 3:22: A graph showing the process of finding the maximum power point

As Figure 3:22 presents the initial process of scanning for the maximum power point, the first step is to scan all the way to V_{oc} in this case it is 12 V, this takes 16.6 milliseconds. The next step is to move the maximum power point which takes a further 5 milliseconds. Perturb and observe algorithm is then used to go to the absolute maximum power point. As seen in the simulation results in Figure 3:21 the ripple that the algorithm causes on the voltage is approximately 0.5 V for both power peaks. This is because the algorithm operates in that manner. It will change the voltage and pay attention to the power; hence the algorithm hovers around the maximum power point.
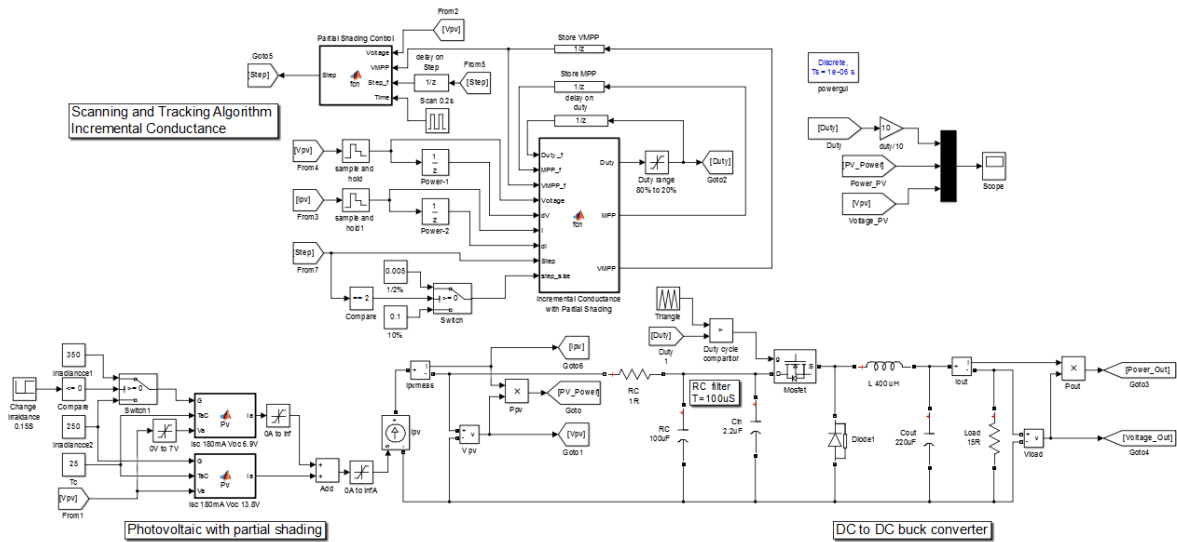
Figure 3:23: Full model with partial shading and incremental conductance algorithm

Figure 3:23 is the full system with the incremental conductance algorithm. The key difference between the two algorithms is that perturb and observe will focus on the power while the incremental conductance on the voltage and current. All the testing conditions are the same as used in perturb and observe algorithm in Figure 3:20.
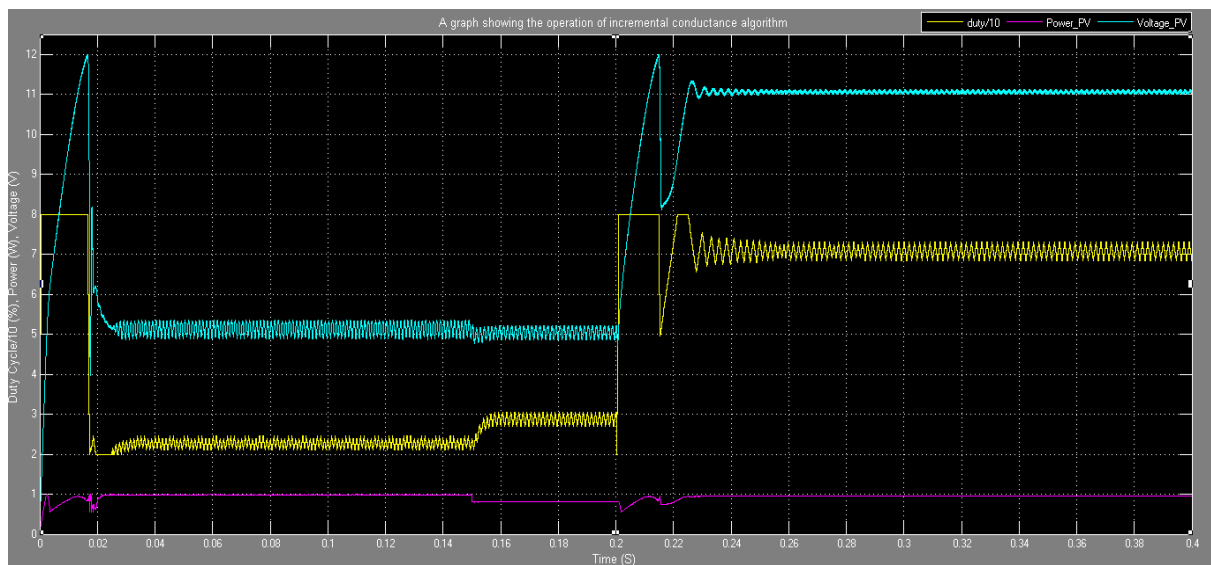
Figure 3:24: A graph showing the simulation results for the incremental conductance algorithm in Figure 3:23

Figure 3:24 is an illustration of how the algorithm incremental conductance operates. This is similar to perturb and observe but with minor differences. Perturb and observe constantly adjusts the duty cycle because of the way it operates. Whereas incremental conductance will not adjust the algorithm if the maximum power point is achieved. This gives an advantage to

66

incremental conductance because the oscillation will be minimal. Table 5 shows the differences between the performances of the two systems.

	Perturb and Observe	Incremental conductance	Units
Finding the Maximum power point	22	24	ms
Change in irradiance	4	8	ms
Voltage oscillation for first peak	0.5	0.45	V
Voltage oscillation for second peak	0.32	0.12	V

Table 5: Comparison between the algorithms perturb and observe and incremental conductance

Looking at Table 5 the results show the perturb and observe algorithm finds the maximum power faster. But the systems efficiency reduces as it keeps track of the maximum power point, because of the oscillation in the voltage. Incremental conductance will take a little longer to obtain the maximum power point. But once it has achieved the maximum power the oscillation on the voltage is less.

4 System design and experiment results

Perturb and observe along with incremental conductance have been modified to locate the true maximum power point in chapter 3 using a simulation package. In this chapter the algorithms will be applied to microcontroller to examine the performance, so the two algorithms can be compared to each other and the simulation.

The photovoltaic modules used in the experiment are 1 W modules, these are single modules, therefore four of them are required to connect together to construct a small photovoltaic panel. The characteristics for photovoltaic panel are as given in Table 6.

Mono-Crystalline Silicon	Conditions	Typical Value	Units
Maximum Power		4	W
Maximum Power Voltage	1,000 W/m²	12	V
Maximum Power Current		340	mA
Open Circuit Voltage	25°C	13.8	V
Short Circuit Current		360	mA
Number of Cells		48	
Size	L, W,D	125*252*3	mm

Table 6: The photovoltaic modules data

Figure 4:1 Is the IV and PV curve for photovoltaic parameters in Table 6 with a 500 W halogen lamp, the irradiance applied is $250\ W/m^2$. The short circuit current obtained is a little over 100 mA and the open circuit voltage is achieved at 11.5 V. The maximum power point is at 10.84 V resulting in a power value of 1.04 W.
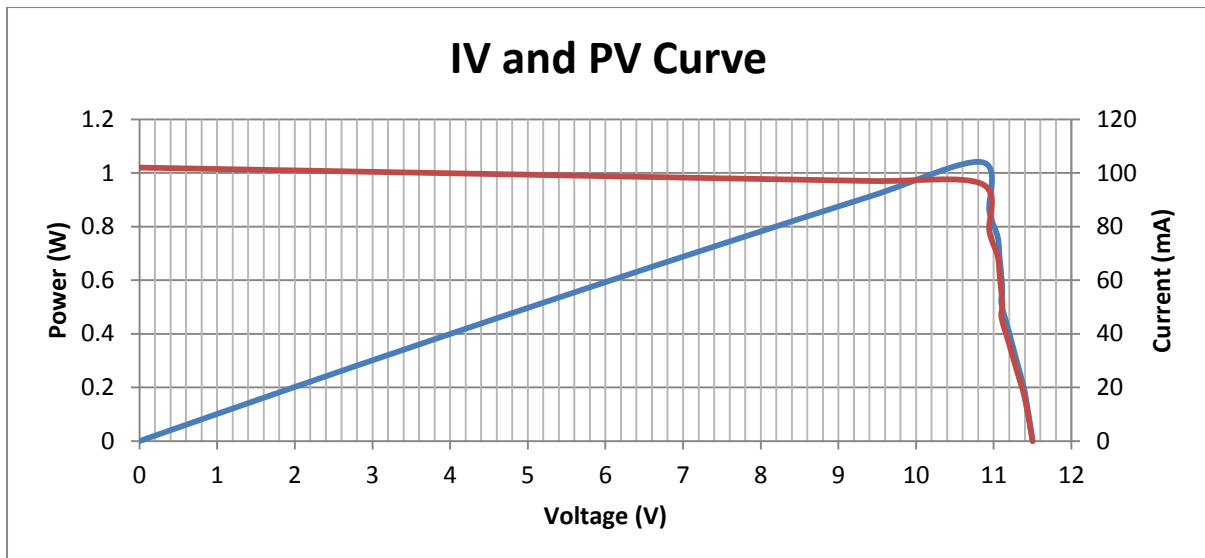
Figure 4:1: The IV curve and the PV curve for the photovoltaics used

The efficiency of the photovoltaic can be calculated using the current data in Figure 4:1 and Table 6. This is given by the power in (Light) divided by the power out as calculated in equation 5.1.

$$\eta = \frac{P_{in}}{P_{out}} \rightarrow \frac{Area * irradiance}{Maximum\ Power} \rightarrow \frac{(0.125*0.252)m^2 * 250\ W/m^2}{1.04\ W} = 7.5\ \% \qquad \text{Eq (5.1)}$$

The efficiency is at 7.5 % therefore the maximum obtainable power will be 1.04 W, with maximum simulated light without any shading.

4.1 Circuit design

The circuit consists of different components put together working as one application. For maximum power point tracking a DC to DC converter is required and to control the converter a micro controller is used. MOSFET is used as switching elements in converters. It requires higher power that the microcontroller cannot supply therefore a driver circuit is inserted at the base.

The microcontroller requires the voltage and current to compute the power and deliver a PWM signal accordingly. It also has the task of controlling the test rig according to the voltages from the phototransistors and to display the information on a LCD.

4.1.1 DC to DC buck converter

The DC to DC converter is used to vary the voltage coming from the photovoltaic, Figure 4:2 diagram of the circuit for a buck converter. A buck converter decreases the voltage

according to the duty cycle. For example if there is a 50 % duty cycle the output voltage is half of what the output voltage is.
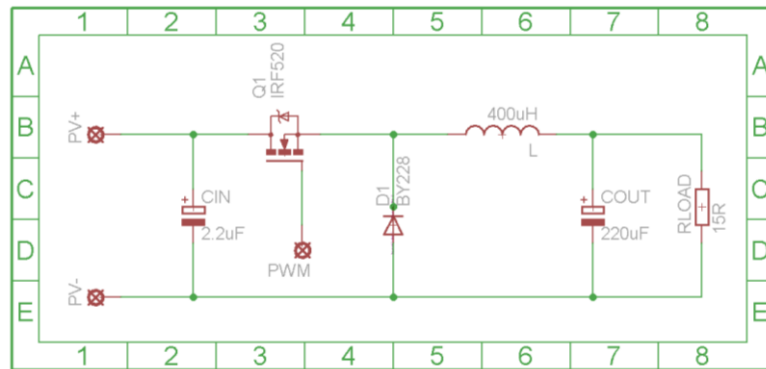
Figure 4:2: A circuit diagram for a DC to DC buck converter

The following formulae calculate each components value.

Component	Equation	Description
C_{in}	$C_{in} = \dfrac{I_{mpp} * T_{on}}{V_{oc}} \rightarrow T_{on} = \dfrac{D}{F}$	I_{mpp} is the current at the maximum power point T_{on} is the time the switch is on which is duty cycle (*D*) over frequency (*F*)
L	$L = \left(\dfrac{1-D}{2*F}\right) * Rload$	D is the duty cycle F is the frequency
C_{out}	$C_{out} = \dfrac{1-D}{8 * L * V_{rip.} * F^2}$	V_{rip} is the ripple on the output voltage. This is small voltage as
R_{load}	20 Ω ≤ R_{load} ≤ 6 Ω	predefined by user

Table 7: Buck converter components calculation

In the Table 7 C_{in} is the input capacitance that the buck converter requires so the input voltage is stable, C_{in} is usually optional. L is the inductor that the buck converter requires to charge and discharge to the output. The inductor must be leaded because the iron core must be charged and discharged. C_{out} is the output capacitance, which will smooth the output voltage across the resistor. This is chosen in accordance with the inductor. If the resistance is too high (above 20 Ω) the inductor size will also be expected to be high. If the resistance is below 6 Ω the inductor would be too small to hold the current.

According to the photovoltaic panel used and measured the following information was obtained:

The short circuit current:

$$I_{sc} = 100 \; mA \; at \; 250 \; \frac{W}{m^2} \qquad \text{Eq (5.2)}$$

The open circuit voltage:

$$V_{oc} = 12.5 \; V \qquad \text{Eq (5.3)}$$

Current and voltage at the maximum power point:

$$I_{mpp} = 90 \; mA \;\; V_{mpp} = 11 \; V \qquad \text{Eq (5.4)}$$

Frequency of the buck converter chosen:

$$F = 10 kHz \qquad \text{Eq (5.5)}$$

Time period:

$$T = \frac{1}{F} => \frac{1}{10e^3 Hz} = 100e^{-6}S \rightarrow 100 \; \mu S \qquad \text{Eq (5.6)}$$

Time on:

$$T_{on} = T * D => 100e^{-6}S * 50\% = 50e^{-6} \rightarrow 50 \; \mu S \qquad \text{Eq (5.7)}$$

Input capacitor measured in nano farads (nF):

$$C_{in} = \frac{I_{mpp} * T_{on}}{V_{oc}} = \frac{90e^{-3} * 50e^{-6}}{12.5} = 0.36e^{-6}F \rightarrow 360 \; nF \qquad \text{Eq (5.8)}$$

Inductor measured in microhenry (µH):

$$L = \left(\frac{1-D}{2*F}\right) * R = \left(\frac{1-0.5}{2*10e^3}\right) * 15 = 375e^{-6} \rightarrow 375 \; \mu H \qquad \text{Eq (5.9)}$$

Output capacitor measured in micro farads (µF):

$$C_{out} = \frac{1-D}{8*L*Vrip*F^2} = \frac{1-0.5 \; S}{8*375e^{-6}*0.01 \; V*10e^3 \; Hz^2} = 166e^{-6}F \rightarrow 166 \; \mu F \qquad \text{Eq (5.10)}$$

Output voltage across the resistor:

$$V_{out} = V_{mpp} * (D) = 11\,V * (0.5) = 5.5\,V \qquad\qquad \text{Eq (5.11)}$$

The closest values for all the components are shown in Figure 4:2. The MOSFET used is an IRF520N, this can handle up to 9.7 A. Which is a lot more than required. However it is powerful enough to handle the current, the PV would provide. The MOSFET used has a very fast switching time; this sharpens the response and accuracy of the buck converter. When the switch is closed the inductor coil is charging, as soon as the switch is opened the inductor gives a spike of voltage known as the back EMF.

4.1.2 MOSFET driver

A microcontroller can supply a maximum current of 25 mA; this can cause an issue when trying to switch on a MOSFET. The driver circuit is an interface between the microcontroller and the converter. This can also be seen as isolation from the converter to the microcontroller. Initially the microcontroller feeds into an opto-coupler; which is a LED shining its light on to a photo-detector isolated from any other light. This transition is made to isolate the microcontroller from the converter. The opto-coupler is then fed into the driver circuit that boosts the voltage and the current. Figure 4:3 shows the inside of the integrated circuit and how there are 2 different power supplies. The PWM signal coming from the microcontroller is inverted by the opto-coupler, which is then inverted again by the driver.
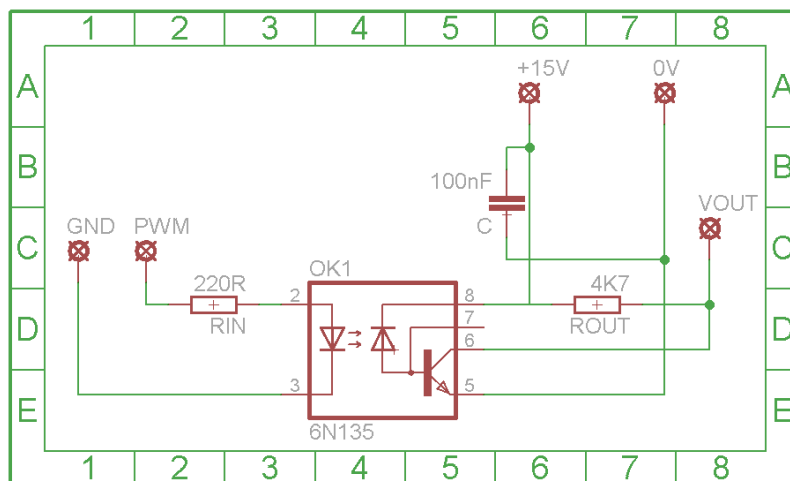
Figure 4:3: Circuit diagram for the opto-coupler

The microcontroller can provide a maximum of 25 mA; in the opto-coupler the LED can only take 1.45 V. Hence a 220 Ω resistor is placed to limit the current to 16 mA. Resistor ROUT is a pull up resistor as prescribed by the datasheet. When the IC is switching the voltage on the power supply may see a ripple; a capacitor is used for smoothing out the power supply. Once the opto-coupler isolates the signal from the microcontroller the PWM signal is boosted

by a driver circuit. This is due to the fact that the opto-coupler can only provide a maximum of 16 mA which may not be enough to switch the MOSFET on.
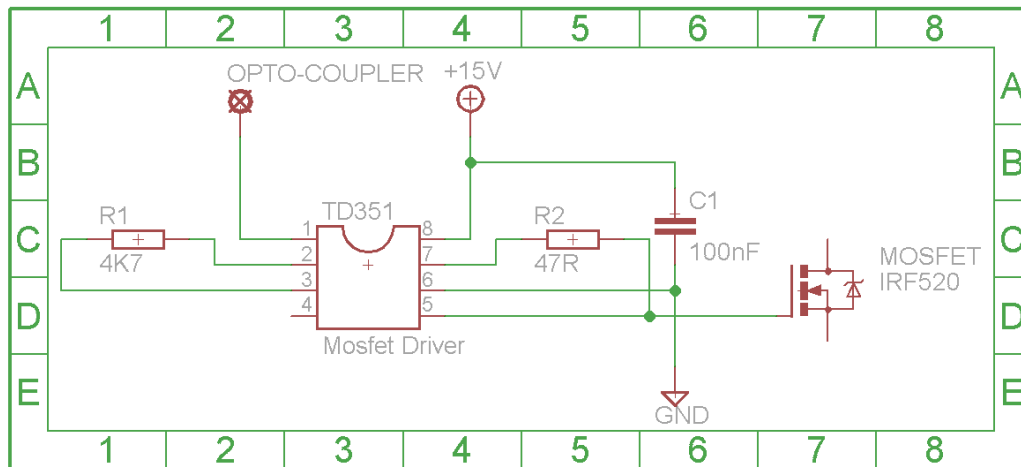
Figure 4:4: The MOSFET and the driver circuit

The driver circuit is implemented to give the MOSFET a good current to ensure it activates. The driver consists of an IC that will boost the current but also has a two level turn off feature that can protect the voltage and current from exceeding the limit. One of the IC components that go hand in hand with the opto-coupler is the TD351. The TD351 doesn't require many external components; this is because the IC package is all inclusive. The power supply is +15 V and ground this gives the PWM the same voltage level as the power supply.

4.1.3 Voltage and current measurement

The traditional method to measure the current with minimal disruption is to use a Hall Effect sensor. A Hall Effect sensor operates in a similar manner to a normal current meter by measuring a voltage across the coil that encircles the wire. For this application the current is not strong enough to be passed through a Hall Effect sensor. Therefore a shunt resister is placed in series and a difference amplifier is used to measure the voltage across the resistor. A difference amplifier measures the difference across the shunt resistor and gives a voltage. Figure 4:5 is the circuit diagram for the difference amplifier.
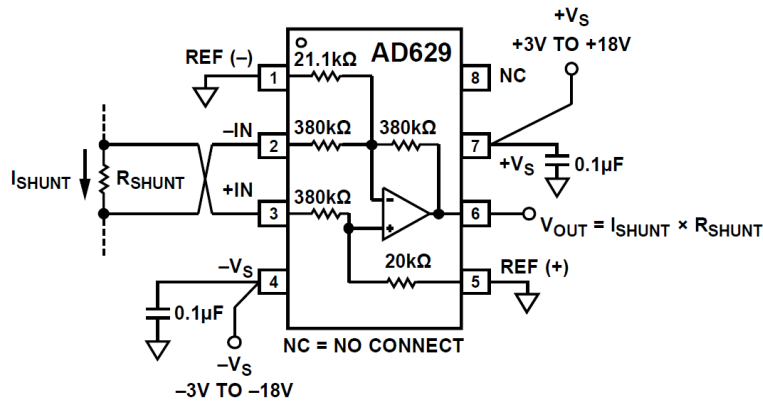
Figure 4:5: The circuit diagram for measuring the current [31]

The voltage V_{out} is given as $R_{shunt} * I_{shunt}$; this is then fed into the analogue to digital converter. The current I_{shunt} is the current that will be measured and the resistor R_{shunt} has a value of 1 Ω. The positive power supply is +15 V and the negative power supply is -15 V.

The voltage range coming from the photovoltaic is 0 V to 14 V. The analogue to digital converters are too expensive to measure the voltage within this range, therefore a proposal is to have three 1 MΩ resistors in series. This will have a gain of 0.3 so the voltage range will be 0 V to 4.67 V; in software the voltage reading can be multiplied by three to obtain the actual voltage. The power that the resistor will take is less than 5 µA; this in effect creates a more cost effective system. Figure 4:6 is the circuit diagram for the voltage and current measuring technique.
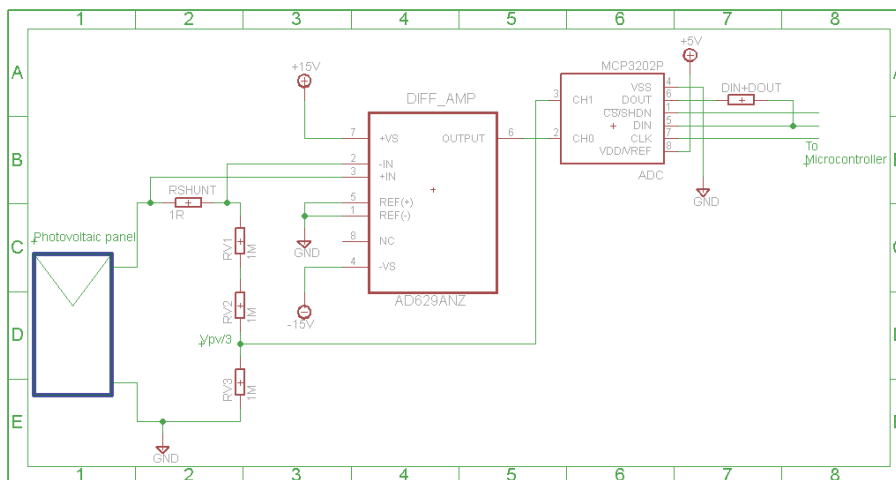
Figure 4:6: A circuit diagram measuring the voltage current coming from the photovoltaic panel

The analogue to digital converter used is manufactured by a microchip called the MCP3202. It has a voltage range of 0 V to 5 V and interfaces with the microcontroller through SPI (Serial Parallel Interface) communication bus. The SPI operates via 4 wires and has a

master-slave operation. As a result in this application the microcontroller is the master and the ADC is the slave. The microcontroller can have more slaves connected and only uses three wires to communicate. The CS pin is the chip select pin which is also controlled by the microcontroller, this allows more slaves as the microcontroller can select which chip it wants to communicate with. The CLK is the clock signal which is driven by the master, on the rising or falling edge of the clock the data is transferred. The data can be transferred via two pins, data in and data out; alternatively they could be tied together with a resistor in between as only one signal will operate at one time, this is implemented in Figure 4:6.

4.1.4 RC filter

An RC filter is a resistor in series and a capacitor in parallel that will smooth the voltage. The capacitor charges up and the resistor smoothly allow the current to pass through. The RC filter uses a small voltage that is across the resistor. Therefore the resistor used has to be the smallest to minimize the volt drop. The switching frequency is 10 KHz so the time constant must be at least 100 µS. The formula for the time constant is given below:

$$\frac{1}{RC} = \frac{1}{1\,\Omega * 100 * 10^{-6}\,F} = 100\,\mu S \qquad \text{Eq (5.12)}$$

4.1.5 Solar tracking

The solar tracking consists of 4 phototransistors at 45^{0} to the photovoltaic panel. One phototransistor is placed facing the right and one towards the left; this is known as the X-direction. One phototransistor is facing up and one down, this is known as the Y-direction. The difference of each direction is fed into an analogue to digital converter where the information is passed on to the microcontroller. A difference amplifier is then used to subtract the voltage of each direction. This could give a negative voltage which the analogue to digital converter cannot operate. Therefore a reference voltage will be added to ensure all readings are in the range of 0 V to 5 V. Figure 4:7 is a diagram of the circuit of the microcontroller to read the voltages on the phototransistors. The power supply to the difference amplifiers are ±15 V.
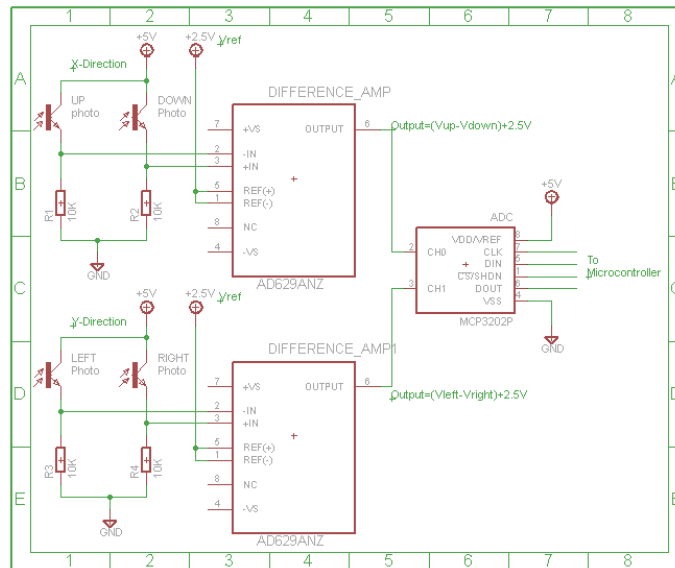
Figure 4:7: The phototransistors circuit diagram

4.1.6 Microcontroller

The microcontroller used is the parallax BS2, this device has been used due to the simplicity in its programming. The simple debugging interface allows easy access to the variables altered in the experimental procedures. The BS2 uses a 16F57c microchip but has its own programming language that is similar to C++. With its unique commands the parallax configures the registers in the microchip with ease. The BS2 uses a 20 MHz processor and has a 2 Kbyte memory which is capable to run the application designed.

4.2 Control algorithms

The algorithm can be split into different segments which are to read the analogue to digital converter, compute for maximum light and controlling the motors, maximum power point tracking algorithm, scanning for multiple peaks and output to LCD. Multiplying the voltage and current can give large numbers that the parallax cannot process. For this a unique technique is used where the first 10 bits of the answer are discarded. This gives a rounded power value. Table 8 illustrates the problems the parallax faces as the power is calculated. The maximum number of bits the parallax can calculate with is 16-bits.

Variable name	Decimal value	Binary value	Number bits required (16-bits max)
Voltage from ADC	4667	1001000111011_{lsb}	13
Voltage x3	14001	11011010110001_{lsb}	14

76

(real voltage value)			
Current from ADC	300	100101100_{lsb}	9
Power (Voltage*Current)	4200300	$10000000001011101101100_{lsb}$	23
Power shifted	4101	1000000000101_{lsb}	13

Table 8: The maximum values used in Parallax

If the power simply multiplied and then shifted the parallax. This would calculate wrongly as it would run out of registers. The proposed method is to divide the voltage into 4-bits at a time and multiply with the current. This captures all the elements and then the split power readings can be added and shifted one at a time.

Formula for power:

$$P = V * I \qquad \text{Eq (5.13)}$$

Microcontroller values calculation for power:

$$V = 14001, I = 300$$
$$P = 14001 * 300 = 4200300 \qquad \text{Eq (5.14)}$$

Real calculation for power:

$$V = 14\,V, I = 300\,mA$$
$$P = V * I \rightarrow 14 * 300 * 10^{-3} = 4.2\,W \qquad \text{Eq (5.15)}$$

Split equation 5.15:

$$P_1 = V_1 * I$$
$$P_2 = V_2 * I$$
$$P_3 = V_3 * I \qquad \text{Eq (5.16)}$$
$$P_4 = V_4 * I$$

$$P_{Total} = (P_1 + (P_2 \ll 4) \gg 8) + (P_3 \gg 2) + (P_4 \ll 2)$$

Example:

$$V = 14001, I = 300, V_1 = 1, V_2 = 11, V_3 = 6, V_4 = 3$$

<div align="right">Eq (5.17)</div>

$$4051\ mW = \big((1 * 300) + (11 * 300) \gg 4\big) \gg 8 + (6 * 300) \gg 2 + ((3 * 300) \ll 2)$$

Equation 5.13 is the official method of calculating power, if it is applied to the parallax microcontroller it will not have the registers to calculate a correct reading. The real world calculation is in equation 5.13 is different to the microcontroller calculation in equation 5.16; this is because the microcontroller will see the current and voltage values as an integer. The proposed calculation will split the voltage into 4-bits and then calculate. Thereafter the power values will be added and shifted 10 times; equation 5.16 gives the formula used. The symbols ">>, <<" indicate the number of places the numbers must be shifted. The example given in equation 5.17 is out by 149 mW, which is acceptable given that the values used are the absolute maximum. When adding and shifting there is a 4 % loss of the power reading.

4.2.1 Analogue to digital converter (ADC)

The ADC's are used to measure a number of parameters to do with the tracking algorithm and the light following. The parallax does not have an ADC onboard so it uses an external converter and communicates through SPI interface as shown in Figure 4:6. SPI uses three wires, clock, data in/out and chips select. Figure 4:8 is the code for the parallax to communicate to the ADC. The parallax uses the command "SHIFTOUT" to select the channel in the ADC. Thereafter the ADC will have a reading for the specific channel ready to be shifted back. The command used for obtaining the value back is "SHIFTIN". Both of these commands use the same setup. The first command will be the data "in/out" pin, and then the "clock" pin is declared; next the parallax needs to know whether the data shifted is MSB or LSB first. Finally the last parameter is the data to be sent or received and how many bits.

```
1  ' {$STAMP BS2}
2  ' {$PBASIC 2.5}
3
4  DIO      CON 12
5  CLK      CON 13
6  CS       CON 11
7
8  adccontrol VAR Nib
9  adcchan VAR    adccontrol.BIT1
10 Value VAR Word
11
12 adccontrol=%1101: adcchan=1
13 LOW CS
14 SHIFTOUT  DIO,CLK,MSBFIRST,[adccontrol\4]
15 SHIFTIN   DIO,CLK,MSBPOST,[Value\12]
16 HIGH CS
17
18 Value=Value*/313
```

Figure 4:8: Parallax program for SPI communication with ADC

Lines four to six are the connections for the ports. Line number eight is the ADC control bits but the channel is declared on line nine. Line nine is also a combination of adccontrol on line eight but only the second bit; this is combined on line 12. The chip select is applied on lines 13 and 16. The command at the end is a calibration formula; this will give a precise value of the voltage measured. There are no decimal numbers in the parallax; therefore a voltage of 2.279 V will be seen as 2279.

4.2.2 Scanning for multiple peaks

In the Simulink model there two sets of code to execute one algorithm, but the microcontroller will run in a continuous manner with an additional variable called "ST" for step. Just as the simulation the algorithm should work in the same principle. In the simulation there are steps to say what to do on each step. For the microcontroller algorithm, this will not be the case, as the code runs line by line. The key task is to run each step for a certain amount of time. The first two steps are not time dependent, they are voltage dependent. The third step is time dependant, for this a time clock can be used to tell the time. The clock can tell the time and every 15 minutes the system can move on to the next step. For test proposes a simple for loop can be used to count to a value that the scanning takes place every 30 seconds. Finally, the last step is to reset and scan again. With the microcontroller the flow code changes but the general core for the execution is the same.
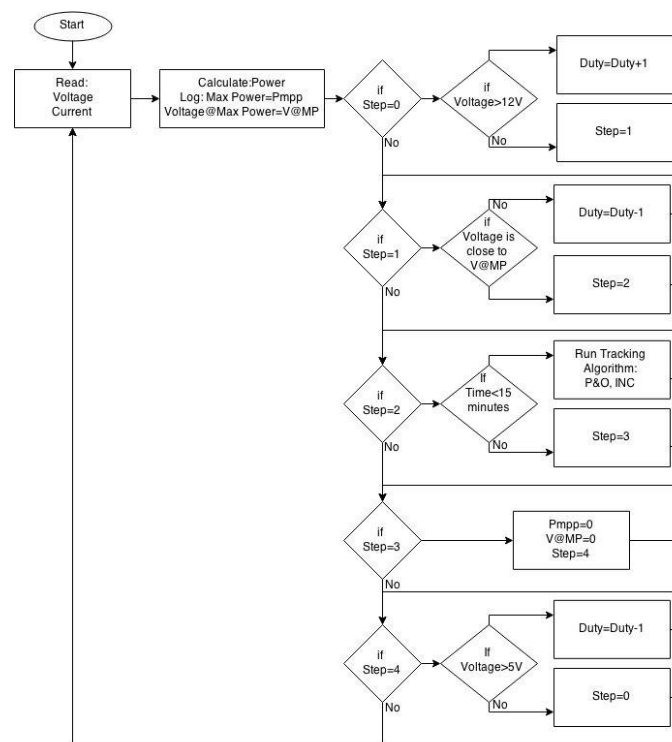

Figure 4:9: A flow code for the tracking algorithm

The flow code in Figure 4:9 tests each step condition as it goes along; whatever the step is only that code will execute and keep reading the voltage and current. As the code returns to the top to read the voltage and current again. It will only execute the step that it was at previously unless the condition was to change the step to the next step. When the algorithm is running in step two it will run for 15 minutes. For test purposes the algorithm will run 2000 times, this is a total duration of 30 seconds.

4.2.3 Perturb and observe

Perturb and observe algorithm can be implemented in parallax. Firstly, the current and the voltage will be sampled and then multiplied to get a power value. The program will then need to check if the power is higher or lower than the previous power reading and adjust the duty cycle accordingly. The program in Figure 4:10 is entered in step two in the flow chart in Figure 4:9 for scanning for multiple peaks.

```
61
62 program_PnO:
63 GOSUB AtoD           ' Read the new power reading
64 IF P<P1 THEN         ' Is the previous power reading higher than the current Power reading?
65     D=D-1            ' The above statement is true (the duty cycle needs to be decreased)
66 ELSE
67     D=D+1            ' The above statement is false (the duty cycle needs to be increased)
68 ENDIF
69 P1=P                 ' Make the current power reading the previous reading
70 RETURN
```

Figure 4:10: Perturb and Observe programmed in the parallax microcontroller

The code on line 62 and 70 is the subroutine that can be called from the main code. The subroutine called on the line 63 is to measure the current and Voltage and to compute the power from the values attained. Lines 64 to 68 is the algorithm perturb and observe, line 64 and 66 are the testing of the two power readings. The variable D is the duty cycle that is increased on line 65 and decreased on line 67.

4.2.4 Incremental conductance

Incremental conductance looks at the voltage and current. Then determines the slope of the power curve. Figure 4:11 is the same as perturb and observe in Figure 4:10 but the algorithm is different. The key difference is clear, as the perturb and observe uses the power to find the maximum power point, but the incremental conductance algorithm uses the voltage and current. Each "If-else" statement tests the condition as shown in the flow code in chapter Incremental conductance in Figure 2:3. The variable "D" is the duty cycle and the variables "V" and "I" are the latest readings coming straight from the analogue to digital converter which is called on line 71. After the program has read the voltage and current it then tests for the maximum power point the current readings become the old readings on lines 93 and 94. This gives a delay between the new readings and old reading.

```
70 program_INC:'------------------------------------------------------------
71 GOSUB AtoD                                    ' Read the Voltage and Current
72   IF (V1-V)=0 THEN                            ' check condition change in voltage equal to zero
73     IF (I1-I)=0 THEN                          ' check condition change in current equal to zero
74       D=D                                     ' No change in Duty cycle
75     ELSE
76         IF (I1-I)>0 THEN                      ' Check if change in current is more than zero
77             D=D+1                             ' increase the duty cycle
78         ELSE
79             D=D-1                             ' decrease the duty cycle
80         ENDIF
81     ENDIF
82   ELSE
83     IF ((I1-I)/(V1-V))=-(I1/V1) THEN          ' is the MPP acheived
84         D=D                                   ' no change in duty cycle
85     ELSE
86         IF ((I1-I)/(V1-V))>(I1/V1) THEN       ' Is MPP to the Left or the Right?
87             D=D-1                             ' decrease the duty cycle
88         ELSE
89             D=D+1                             ' increase the duty cycle
90         ENDIF
91     ENDIF
92   ENDIF
93   V1=V                                        ' dv=V
94   I1=I                                        ' dv=I
95 RETURN                                        ' End
```

Figure 4:11: The incremental conductance algorithm implemented in the parallax microcontroller

The algorithm is run line by line so the first statement that will be tests if the voltage has changed. If it hasn't changed the algorithm checks if the current has changed. If it has then the algorithm determines whether the current change is positive or negative. If there is a change in the voltage the algorithm is to check the ratio in the change and adjusts the duty cycle accordingly.

4.2.5 LCD

The Liquid Crystal Display is used to display the some parameters that the user can verify with the algorithms results. The size of the LCD has 32 characters on two rows. The diagram in Figure 4:12 split the LCD to display as much information as possible. Firstly, on the top left the algorithm is displayed. This can "INC" for incremental conductance or "P&O" which is perturb and observe. In the middle of top row is the power measured in mW and the left is displaying the duty cycle in percentage. The bottom row on the left displays the angle the photovoltaic is tilted at, next to it is the direction the photovoltaic is facing. On the right of the bottom row the global peak voltage is displayed.

I	N	C		P	1	0	1	5	m	W		D	6	2	%
A	4	8		S	W	S		G	P	1	0	.	9	5	V

Figure 4:12: LCD display

The parallax has a command that will easily write to the LCD. The command is "SEROUT"; this will configure the LCD and thereafter write to the screen. To configure the LCD the command is "SEROUT LCD,$4054,[254,1]", LCD is a connection on pin 10, "$4054" is the

81

baud rate which is passed over to the LCD display first. The square brackets hold the information to send over to the LCD display. Now the LCD is ready to be passed information to write on the screen. For this the same command is used but the square brackets hold the characters or variable to send to the LCD display.

4.2.6 Pulse width modulation

The switching frequency is 10 KHz, this fed into the opto-coupler and then to the buck converter. The parallax microcontroller has a function for altering the pulse width modulation. But this operation is only executed at one frequency of 200 Hz. Higher frequencies are available but the parallax will not alter the duty cycle. Therefore a microchip is used generate a 10 KHz frequency and the duty cycle is altered by the parallax. The PIC chip uses 8-bits to alter the duty cycle; hence eight signals going from the parallax to the PIC chip as illustrated in Figure 4:13
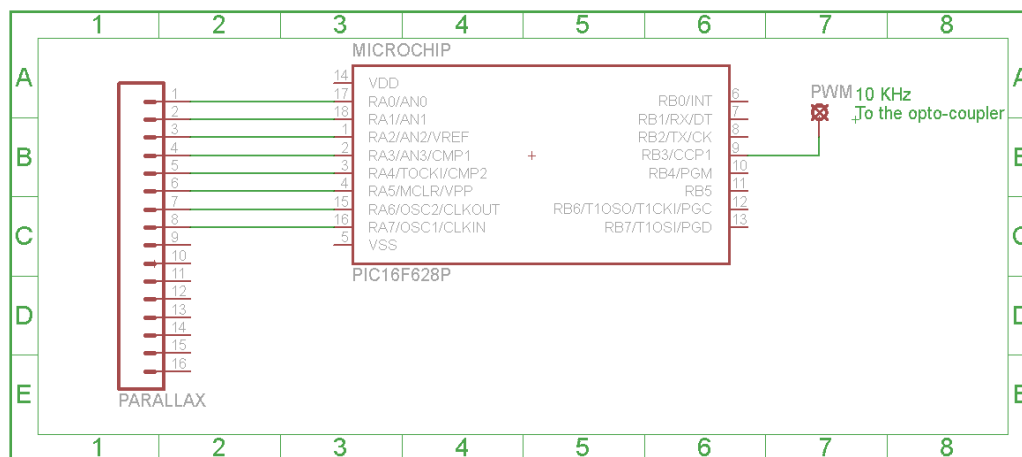
Figure 4:13: Circuit diagram for the PWM

The flowchart and the program in Figure 4:14 are programmed into the microchip. This produces a 10 KHz frequency with the duty cycle information passed from the parallax to the PIC chip. Lines 1 to 13 are setting up the PIC chip. Lines 15 to 18 are writing the data from the Port A to the duty cycle register. The PIC chip uses a counter to count to a value of 99, as soon as the counter reaches the value of CCPR1L, which is the duty cycle, the comparator pin will switch from logic high to logic low. When the counter value reaches 99 the counter resets and the output of the comparator switches back to a logic high.

Figure 4:14: Software for the PWM generator

The parallax side just passes the information over to the microchip; it also has an upper and lower limit programmed. The code checks if the value exceeds the upper limit which is 80, if so then the code will dictate a new value which is slightly lower and the same for the lower limit. The limits are for the buck converter; the buck can only handle an upper of 80 % and a lower limit of 20 % duty cycle. This is because the inductor coil requires at least a little power to charge and discharge.

4.3 Concentrated photovoltaic

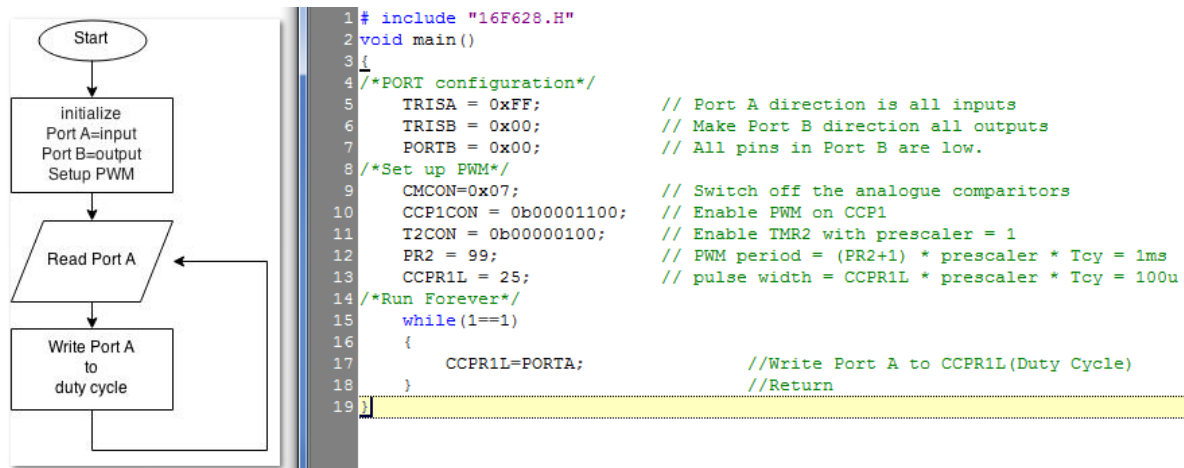On a fixed photovoltaic the sun will shine at an angle, this lowers the efficiency of the overall system. The method used to track the most amount of the sun light will be determined by phototransistors strategically placed around the photovoltaic. This will indicate that the motors are required to track the most amount of sun light. The phototransistors are placed at 45º to one another as Figure 4:15 illustrates

The difference amplifiers will subtract the voltages from each other, this will reduce the number of ports required, and the processing will take less time, giving the maximum power point tracking algorithm more processing preference. Firstly, the code will read the voltages of both X-direction and Y-direction; the voltage should read 2500 for 2.5 V. At all times the light should be at 0º to the photovoltaic panel. Figure 4:15 shows what the readings will be if the sun light is at different angles to the phototransistors. The phototransistors can only see the light if it is 60º in front of it. Therefore at ± 25º the voltage changes, at 45º the light directly in front of the phototransistor, so it is at its highest value. If the light is more than ± 45º the voltage will go gradually back to 2.5 V.
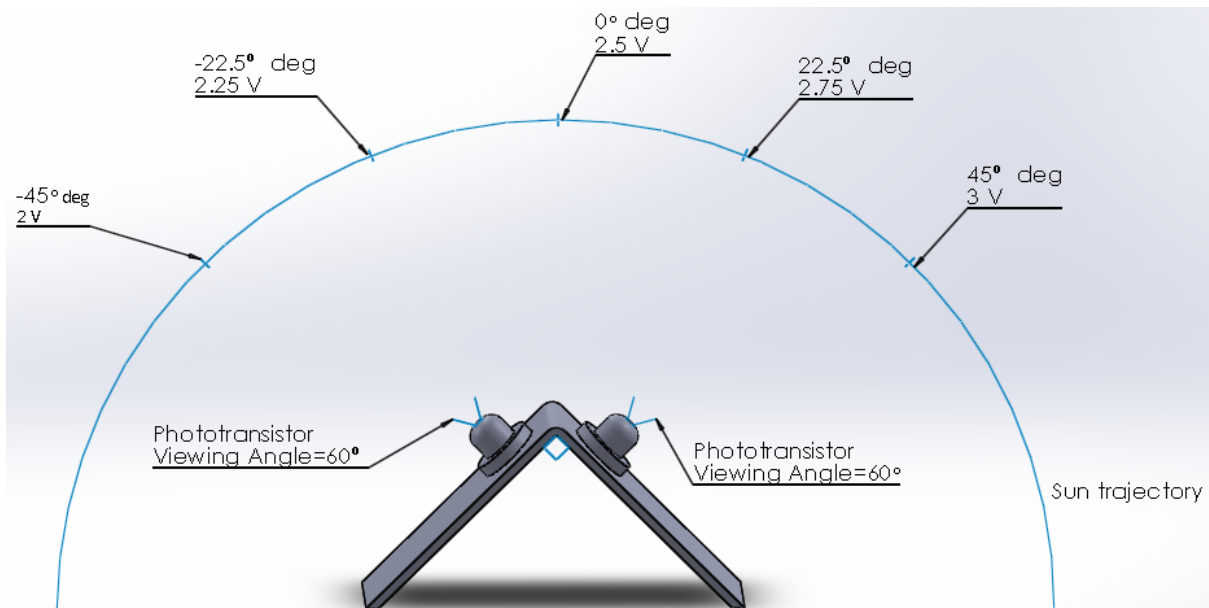
83

Figure 4:15: Phototransistors voltages level according to sun position

The motors are limited to a 180º rotation, which is sufficient because the direction will only be required to go from east to west; and the Y-direction requires a 90º rotation. The motors are controlled by the parallax which has a single command that will move them. The command is "PULSOUT", this only requires two parameter, the port number and the duration of the pulse that will be on. The duration will be altered according to the readings from the phototransistors.

4.4 Results and comments

The parallax microprocessor uses a 20 MHz clock. The program has a lot of test conditions so every 15 milliseconds the new duty cycle is updated, this delays the overall system response time. The total response time is when the maximum power point is achieved. The partial shading scanning process will take 800 milliseconds to locate the maximum power point and take the system close to the maximum power. The algorithm will then run and deliver the absolute maximum power point.

Both algorithm operate in a similar manner, when the irradiance are high the duty cycle will be high, when the irradiance are low the duty cycle will be low. Figure 4:16 has the light switched on at its minimum level, with the perturb and observe algorithm the parameters are as follows: $V_{mpp} = 10.916\,V$, $I_{mpp} = 120\,mA$ and $P = 1.3\,W$. The irradiance is approximated to $316\,W/m^2$ making the photovoltaic efficiency 7.5 %.The efficiency of the converter is 81 % at 40 % duty cycle. The losses of the converter are due to heat dissipated by the components in this case it is 0.25 W.

Perturb and Observe Algorithm controlling a Buck Converter and a small photovoltaic panel at low irradiance

Figure 4:16: Low irradiance applied to the photovoltaic with perturb and observe algorithm

In Figure 4:17 the light is increased to maximum light available from the halogen lamp. The system is expected to increase the duty cycle to accommodate more current. The efficiency of the photovoltaic will always stay the same because of the properties of the material used in the photovoltaic. However, the power does increase to 2.8 W with $673\ W/m^2$ applied to the photovoltaic and the duty cycle increases to 65 %. As the duty cycle increases the efficiency of the buck converter also increase bringing it to 86 %. The power losses due to heat dissipation increases also as there is more current passing through the components.

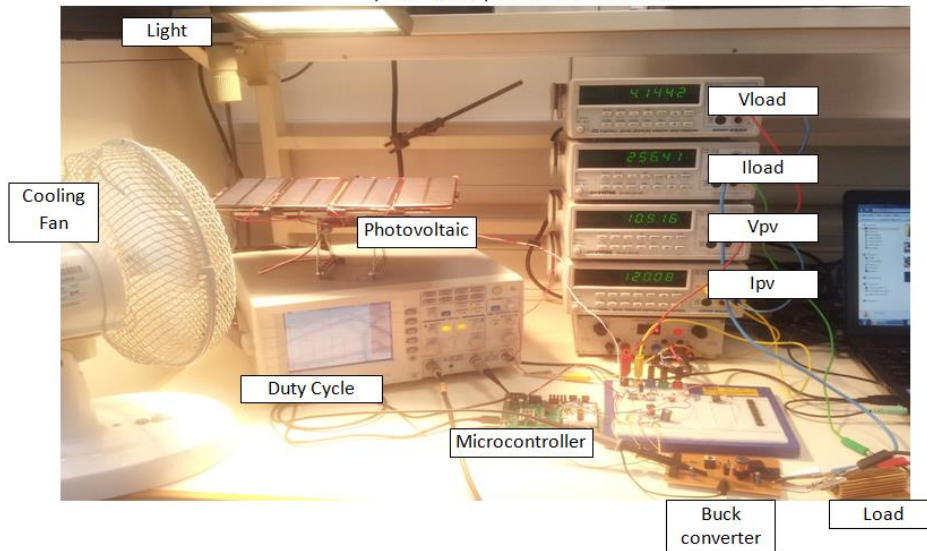Perturb and Observe Algorithm controlling a Buck Converter and a small photovoltaic panel at high irradiance
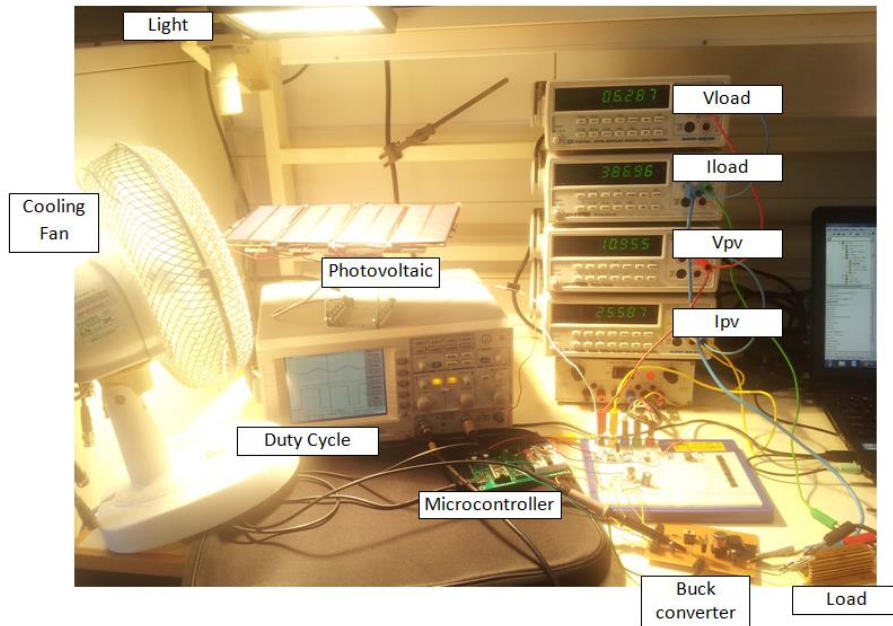
Figure 4:17: High irradiance applied to the photovoltaic with perturb and observe algorithm

The algorithm incremental conductance algorithm is applied with low level of irradiance and high level of irradiance. The duty cycle should start low for low irradiance and increase as the irradiance increases. Figure 4:18 has a low level of irradiance shining on the photovoltaic with the incremental conductance algorithm operating on the microcontroller. The power that the photovoltaic is providing is 1.45 W with $345\ W/m^2$ and the duty cycle that the algorithm computes is 42 %. As with the perturb and observe algorithm the converters efficiency is 81 %, also the looses due to heat dissipation are very similar at 0.28 W.

Figure 4:18: Low irradiance applied to the photovoltaic with incremental conductance algorithm

In Figure 4:19 the irradiance are turned to the maximum available via the halogen lamp which is $632\ W/m^2$. The incremental conductance algorithm extracts 2.6 W from the photovoltaic. The efficiency of the converter is 86 % at a duty cycle of 63 %.
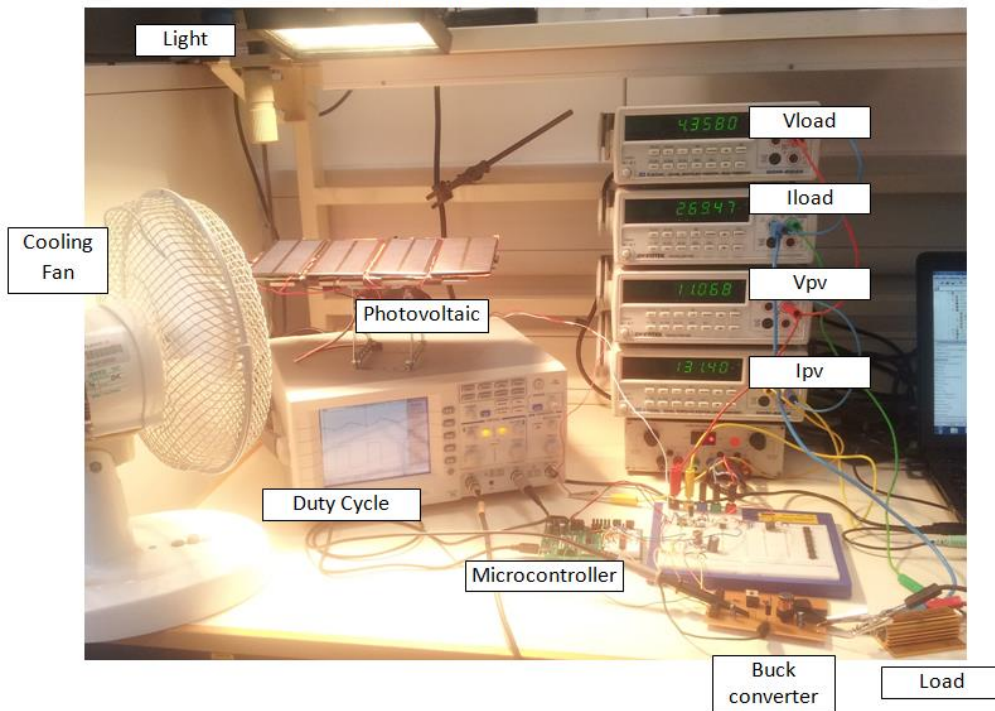
Figure 4:19: High irradiance applied to the photovoltaic with incremental conductance algorithm

Although the irradiance are not exactly the same as one applied in Figure 4:16 and Figure 4:18, the comparison can be made because the two current readings don't have too much difference between them. The perturb and observe algorithm finds the maximum power point in 0.5 seconds. Whereas the incremental conductance algorithm finds the maximum power point in 0.6 seconds. In this case the perturb work better because the incremental conductance has a lot of test conditions. The incremental conductance takes more time computing for the duty cycle whereas, the perturb and observe algorithm takes less time computing.

The partial shading process takes 0.5 seconds to find the maximum power point and take the system close to the maximum power voltage. The algorithm then takes over and focuses on delivering the maximum power. Figure 4:20 shows the microcontroller finding the maximum power. The time per division is 2 V per square, and the voltage increases from 0 V to 12 V, then to the maximum power point. The solar tracking system with the test rig finds the maximum sun light within one second.

Figure 4:20: Partial shading voltages with 2 different conditions

5   Conclusion

5.1 Review of objectives and achievements

In conclusion the study investigated the algorithms performance when partial shading develops and movement of the solar tracker.

Objectives:

Solar tracker:

1. Movement of the motors: Servo motors used to move the platform every time the sun deviates by 25 deg.
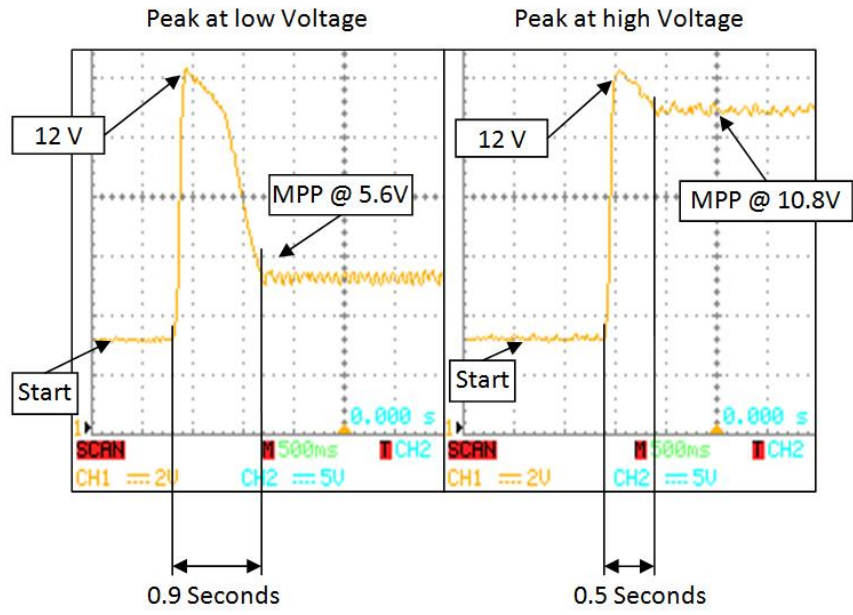2. Technique of sensing the direction of light intensity: Using sensors at 45 degrees facing up, down left and right. Explained in more detail in "3.2 Concentrated photovoltaic".

Maximum power point tracking:

1. Partial shading accommodated algorithms: The entire I-V curve is scanned to perceive the location of the global peak. The once located the conventional algorithms operate to achieve the maximum power point.
2. In terms of performance which of the two algorithms operates more efficiently: Perturb and observe algorithm operates better because it has less calculation than incremental conductance and therefore finds the peak faster.
3. Control circuitry power consumption and cost: The control circuitry cost is approximately £45. This is including the DC to DC buck convertor, the voltage and current sensors also the microcontroller. In order to reduce the circuit power consumption, low power components were acquired and this achieved a total energy consumption of 0.645 W

5.2 Conclusions

Compared to the conventional systems the response time is slow however, this has been implemented with a basic microcontroller. With that comparison the conventional systems are using advanced microcontrollers.

The control circuitry and driver circuit included consumes a total of 0.645 W. The photovoltaic can provide this along with a boost converter because the MOSFET driver requires 15 V, but without the load. Also the load is a constant resistor but in an ideal system, the power would go straight into a DC to AC converter. This current system can handle up to 2 A, therefore the larger photovoltaic can be used with the same converter.

Larger panels can provide the power to the control circuit as well. However super capacitors can be used to power the control circuit as they require very little time to charge and can slowly provide power to the control circuit.

The concentrated photovoltaic only moves once the light is intense on one side of the sensor. This is at approximately 25º to the panel. Therefore on an average day the sun will go from east to west (180º) the motor controlling the direction will have to move 7 times a day. In Manchester, United Kingdom the sun will rise to 36º, so the angle motor will have to move 4 times a day totalling 11 times on an average day.

The controller circuit that consisting of microcontroller, voltage and current measurement and the driver takes 43 mA. The motors used for the concentrated photovoltaic take 140 mA each. This would require additional power but only when the motors required to be moved. For example the motors are moved when the light is more than 25º. Currently an external power supply is providing the electricity and is only for test purposes. The control circuit is using little power but the photovoltaic will struggle to maintain this power and supply the buck converter. Hence a super capacitor can be used to provide the electricity to the control circuit. A super capacitor can charge very fast and discharge gradually. When the charge in the super capacitor starts to drop the photovoltaic can charge the capacitor then carry on supplying the buck converter. This way no batteries or external power supply is required.

5.3 Future work

As proved in the results incremental conductance is slower and less efficient than perturb and observe. Both of these algorithms can be enhanced to improve the speed and accuracy to obtain the maximum power point. The partial shading scanning process can also be enhanced to scan faster and to return to the maximum power point.

In the design

Table 4 the steps are clearly stated to scan and return to the maximum power point. When the algorithm is running and there is a change in the irradiance as in the power level has changed, the algorithm can scan the entire power spectrum to see if there is a new global peak. Figure 5:1 is a flow chart showing how the program will operate; the section in red indicates the added improvements. The added feature may cause a problem to the system in the real world. This is because the change in irradiance is completely random; the algorithm can keep looking for the maximum power peak and not delivering the maximum power at all.
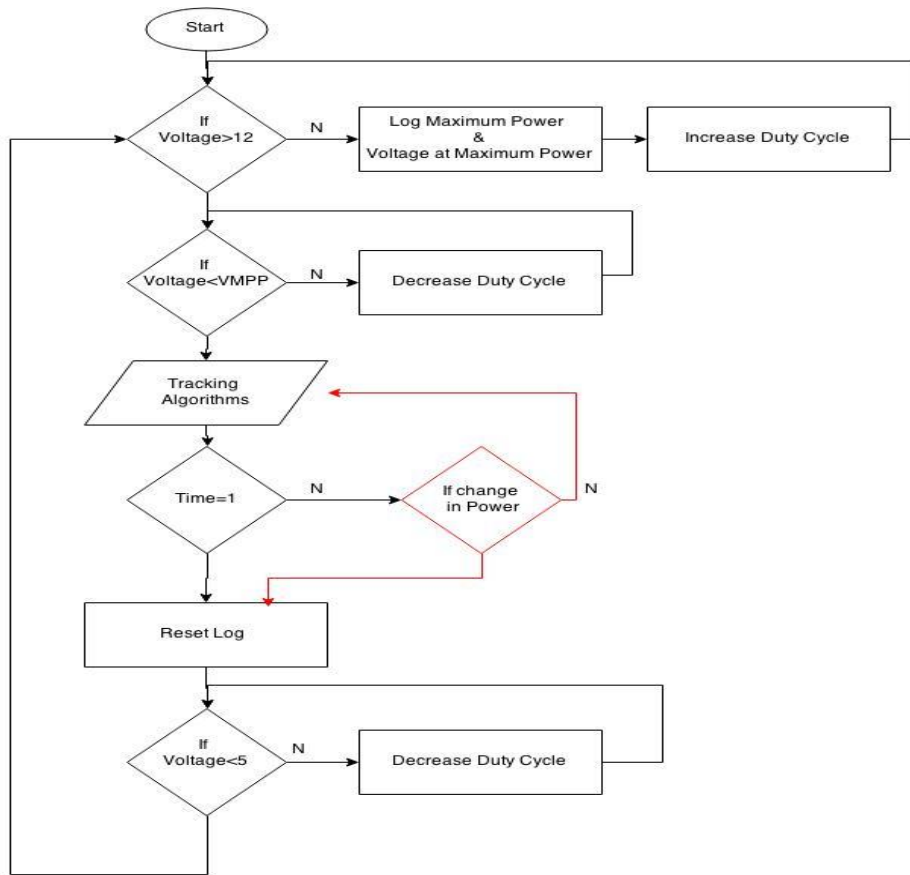
Figure 5:1: A flow chart showing future improvements the algorithms

Another enhancement is to speed the process of scanning for the peaks. Currently if the global peak is at a higher voltage the system will go to a lower voltage then scan to the high voltage again. This is an unnecessary process as the scan is only needed once for completion, thereafter making the algorithm find the global peak faster.

In the practical improvements a better microprocessor can be used, although the parallax uses a 20 MHz processor it does not execute the program at that frequency. Also time is lost while communicating through SPI for the voltage and current readings. A faster approach would be to have a parallel communication port. So the improved version will need more ports and a faster processor.

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