

# **Power Load Optimization in a Wireless Communication System in Remote Area**

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## **ABSTRACT**

Obtaining the maximum power is a very important issue in self-powered wireless systems, especially for those fed by solar panels. Solar energy is one of the most significant renewable energy sources which has no pollution and does not make any noise, and because of these advantages using solar energy is increasing rapidly. This thesis is written under the research project called Integrated Homeland Security Surveillance System (IHSS).

IHSS is a multipurpose security surveillance system fed by solar energy; this thesis follows the project limitation and objectives. In systems which use photovoltaic (PV) panels as power source, obtaining the maximum power is essential. There are many methods to optimize energy drawn by solar panels; maximum power point tracking (MPPT) is one of the methods which widely used to optimize system performance. There are also several algorithms for maximum power point tracking, but each of those methods has its own problems in speed and accuracy, and they couldn't improve both factors simultaneously. Among those methods, Hill Climbing method has the most acceptable speed and accuracy, but still can't deliver both factors simultaneously.

In this thesis, we propose to employ novel techniques to improve the optimum power tracking using the Hill Climbing method. MATLAB/Simulink simulation platform will be used for the simulation. The current work can also be used in other applications using photovoltaic technology, especially in MPPT.

**Keywords:** solar panel, photovoltaic, maximum power Point tracking, power optimization, wireless communication system, renewable energy

## ÖZ

Özellikle güneş panelleri tarafından beslenen sistemler olmak üzere, kendi kendini besleyen kablosuz sistemlerde , maksimum gücün elde edilmesi oldukça önemli bir konuyu oluşturmaktadır. Güneş enerjisi, herhangi bir kirliliği olmayan ve hiçbir gürültüye neden olmayan en önemli yenilenebilir enerji kaynaklarından biri olup bu avantajlarından dolayı güneş enerjisinin kullanımı hızlı bir şekilde artmaktadır. Bu tez çalışması Entegre Ülke Güvenlik Gözetleme Sistemi (EÜGS) (Integrated Homeland Security Surveillance System – IHSSS - ) konulu araştırma projesi kapsamında hazırlanmıştır.

EÜGS güneş enerjisi ile beslenen çok amaçlı bir gözetleme sistemi olup bu tez çalışması proje sınırlamaları ve amaçlarını takip etmektedir. Güç kaynağı olarak güneş panellerini kullanan sistemlerde maksimum gücün elde edilmesi gerekmektedir. Güneş panelleri tarafından üretilen enerjinin iyileştirilmesi için birçok yöntem mevcut olup Maksimum Güç Noktası İzleme Yöntemi (MGNİY) (Maximum Power Point Tracking – MPPT - ) sistem performansının iyileştirilmesi için oldukça yaygın bir şekilde kullanılan bir yöntemdir. Ayrıca maksimum güç noktasının izlenmesi için birçok algoritma kullanılmakta olup ancak bu yöntemlerin her birinin hız ve doğruluk açılarından kendine özel problemleri bulunmakta ve aynı zamanda her iki faktörü sağlayamamaktadırlar.

Bu tez çalışmasında Yüksek Tırmanış Yöntemi (Hill climbing Method ) kullanılarak optimum güç izleniminin geliştirilmesi için yenilikçi tekniklerin kullanılması amaçlanmaktadır. Simülasyon için MATLAB/SIMULINK platformu kullanılmıştır.

Bu çalışma özellikle Maksimum Güç İzleme olmak üzere güneş enerjisinden yararlanan diğer uygulamalarda da kullanılabilir.

**Anahtar Kelimeler** : Güneş paneli, fotovoltaik, maksimum güç izleme, güç optimizasyonu, kablosuz haberleşme sistemi, yenilenebilir enerji

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Dedicated to  
My  
Beloved Parents



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## **LIST OF SYMBOLS/ABBREVIATIONS**

AC	Alternate Current
Dc	Direct Current
IHSSS	Integrated Homeland Security Surveillance System
INC	Incremental Conductance
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P&O	Perturb & Observe
PV	Photovoltaic
SMPS	Switching Mode Power Supply
STC	Standard Testing Condition

$I_{mp}$	Current at maximum power point
$I_{ph}$	Photo-current
$I_{pv}$	Current of photovoltaic panel
$I_s$	Reverse saturation current
$I_{sc}$	Short Circuit current
$K$	Boltzmann constant
$n$	Diode Ideality Factor
$P_{pv}$	Power of photovoltaic panel
$P_{mp}$	Power at maximum power point
$q$	Electron charge
$R_{se}$	Series resistance
$R_{sh}$	Shunt resistance
$S$	Irradiance level
$T$	Temperature
$V_{mp}$	Voltage at maximum power point
$V_{oc}$	Open Circuit Voltage
$V_{pv}$	Voltage of photovoltaic panel
$V_t$	Thermal voltage



# Chapter 1

## INTRODUCTION

### 1.1 Overview of study

World economies depend on a reducing resource of limited, environmentally unfriendly, and non-renewable fossil fuels. Nowadays the search for clean alternative energy became a very hot political, economic and social urgent due to concern of global warming, climate change and economic recession. Non-renewable Hydrocarbon fossil fuels are the number one pollutants of our atmosphere and they are running out fast. This resource must be superseded by renewable energy resources, and solar energy is the highest potential energy source in the world, but not the most efficient one [12]. The light energy is harvested by solar cells with no environmental pollution, but it has a high production cost and low energy conversion efficiency which are the two most significant drawbacks in developing solar systems [4].

The output power of a solar panel always changes by environmental conditions like intensity of sun radiation, environment temperature, and also loads current. To overcome these nonlinear characteristics many solutions have been proposed. Some of them focused on to control the input to solar panel by using sun-tracking systems [1-3]. Others used techniques to track maximum power operating point of the system and force the system to operate toward this condition [4-7]. Many MPPT methods

have been studied and implemented. Out of those, Hill climbing method is the best in speed and accuracy for our application, but still can't give both factors together.

This Thesis is a part of a project called Integrated Homeland Security Surveillance System (IHSS) [8].

IHSS project consists of processors, camera(s) and batteries which charged by solar energy. The aim of IHSS project is producing a self-powered system consist of modules in order to make a multipurpose surveillance system to increase situation awareness and improve the crisis management in cases of terrorism, natural hazards and human trafficking. The modules of IHSS project are completely self-powered, and because of that, power optimization is became a vital issue in this project. In this thesis, we introduce novel techniques to improve the optimum power tracking based on the Incremental Conductance method, in order to optimize the power in IHSS project.

## **1.2 Photovoltaic Technology**

The first silicon PV cell has developed by scientists at Bell Labs in 1954 and the first usage of solar cell was for space applications [13]. Normal use of solar cells started from 1970s, and today we use it in many applications, from scientific calculators through home applications, to solar power stations. Photovoltaic energy significance is increasing day by day, and it's going to play more important role to provide the needs of electricity in this century [13]. A solar cell or a photovoltaic (PV) cell is a semiconductor that converts the light energy to the electricity [Figure 1-1].



Figure 1-1: Silicon solar cells packaged in module

A typical solar cell is made from single p-n junction silicon which has a p-type silicon base and an n-type top layer [Figure 1-2]. This junction is able to create electrical energy directly from the light photons by making a voltage potential in junction. If we connect a load to the cell, a direct current (dc) will be flow through the load.

Most of panels comprise 72 crystalline silicon cells which able to produce about 160W at 36 volts. A set of panels which connected in series make a string.

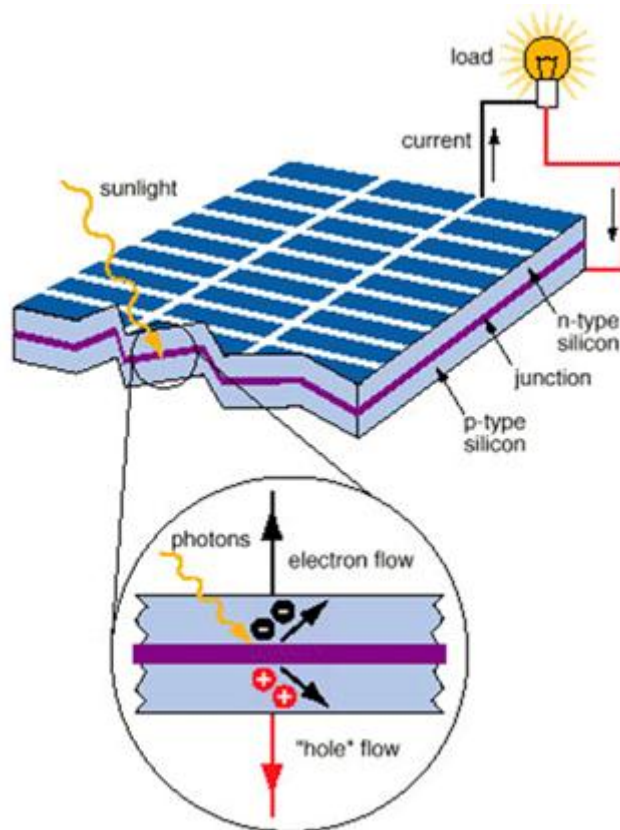


Figure 1-2: Typical p-n junction solar cell

During the years, solar photovoltaic technologies usage grows about 40% yearly [10], but almost all of the solar cells have been made by silicon. Despite the developments in manufacturing techniques, 80% of solar cells are still made by silicon [9, 13], but there are several different technologies in this market.

### 1.3 Types of solar cell

Silicon is the favorite substance to build solar cells, because it's the most available material on the earth to make it. The two major types of solar cells are made by single-crystal silicon and poly-crystal silicon, and the third type is amorphous silicon but it's not very popular due to its low efficiency. Despite many efforts to use new materials in building new solar cells, still there is no commercial different solar cell. Here is a short review of these three popular kinds of solar cells.

### **1.3.1 Single-crystalline silicon**

Single-crystal silicon or Mono-crystalline silicon solar cells are the most common type of solar cells with efficiency up to about 17% [14]. They are cut from cylinders up to 30 cm diameter in very thin slices, and because of that they called wafers. Single-crystal wafer cells are almost expensive (around \$200 for a 300 mm Si wafer) due to their careful operation of manufacturing which should be done in high temperature [15, 17].

Almost 7 m<sup>2</sup> of mono-crystalline silicon is needed to obtain 1KW electrical energy in Standard Test Conditions (STC) which is the testing conditions to measure the nominal output of solar cells. In STC, Irradiance level is 1000 W/m<sup>2</sup>, with solar spectrum of 1.5 air mass and cell temperature must be 25°C.

### **1.3.2 Poly-silicon**

Poly-silicon, also called polycrystalline is also made from wafers of pure silicon, but its crystal structure differs from mono-crystalline crystal structure [Figure 1-3 (b)]. The poly-crystalline crystals are different in shape, size, and direction. This structure gives us less efficiency (11-15%) but it also cost less [16]. Almost 8 m<sup>2</sup> of poly-crystalline silicon is needed to obtain 1KW electricity in standard test conditions.

### **1.3.3 Amorphous Silicon**

Amorphous silicon (a-si) have been used in applications with low power consumption, like calculators, since 1980s, because their efficiency is lower than poly-silicones and single-silicones (around 6-8%), but it is also cheaper than those two [16]. The major difference of amorphous silicon by single-crystalline and poly-crystalline silicon is in its non-crystalline structure which makes it cheaper than two others because the producing procedure runs in lower temperature which makes it

easier and simpler than the other ones. It also can be sandwiched between two layers of glass and it reduce the amount of requiring material to build a solar cell which is the largest factor in manufacturing, but it also make amorphous silicon panels much heavier than the crystalline ones. Despite the low efficiency, amorphous silicones have the better performance in compare to crystalline panels in cloudy days [9]. The other important property of amorphous cells is their flexibility [Figure 1-3 (a)]

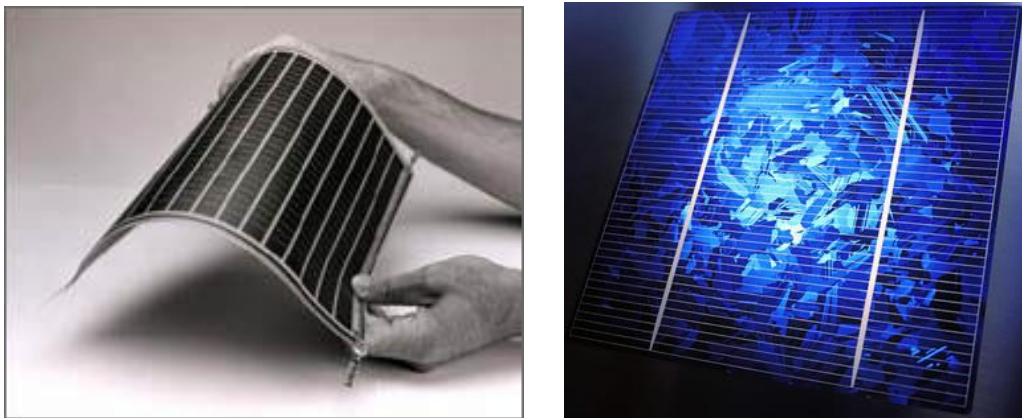


Figure 1-3: (a): Flexible amorphous cell (b): Poly-crystalline solar panel

## **1.4 Types of Solar Power System**

Solar power systems can be classified in terms of their connection to the electrical grid.

### **1.4.1 Grid-connected photovoltaic power System**

A grid-connected photovoltaic power system is a photovoltaic system which connected to public electrical grid and delivers the power to the grid. A grid-connected system can be a residential system or a solar planet. The most advantage of grid-connected system is that they don't need battery storage which is expensive [21]. But they need inverters to convert the Direct Current (DC) produced by solar panels to the desired frequency of Alternative Current (AC) which runs in utility grid. These investors also play a significant role in overall efficiency of system.

### 1.4.2 Stand-alone Photovoltaic Power System

The primary implementation of solar power system was in stand-alone power systems in remote areas which electrical grid was not available. They are also use in many applications from calculators to spaceships. Stand-alone photovoltaic power systems are limited by battery storage capacity and excess power will be wasted if the batteries were full. This makes the stand- alone power systems less efficient in compare with grid-connected ones, which able to deliver the excess power to the grid [21]. However sometimes they coupled directly to the load, but as the power requirement by load is not always equal to the power produced by solar panel; the direct coupling is not very common and the produced power should firstly store in a battery bank. When the batteries come, they brings another problem, the weight of batteries can be a problem, especially in mobile applications. A controlling unite also may be needed to control the charging process, to prevent the possible damage due to overcharging.

Stand-alone solar systems also need an inventor if they supply an AC load [Figure 1-4]. These types of power systems sometimes built in a hybrid form combine with a diesel generator or wind turbine.

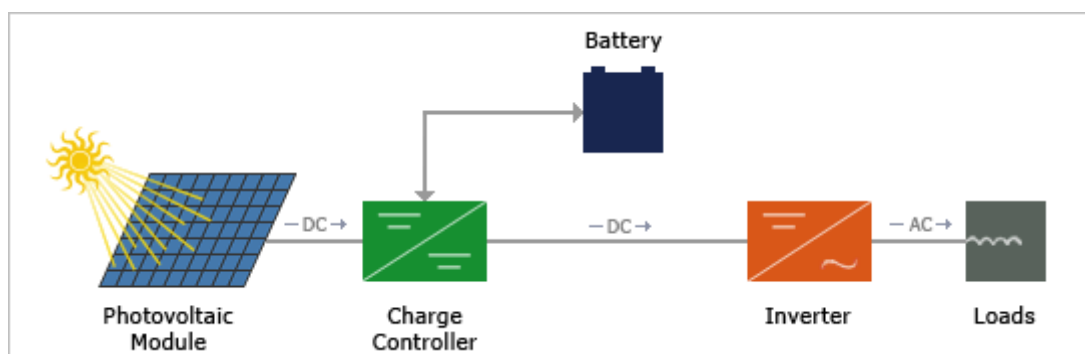


Figure 1-4: A solar system powering AC loads with battery bank, charge controller and inverter.

The IHSSS project modules are also powering by a stand-alone power system, in according to their remote application.

### **1.5 Drawbacks of photovoltaic technology**

The major drawback of the photovoltaic technology is its low efficiency which has effect on many other important characteristics in applications. High cost of photovoltaic technology directly, affected by its low efficiency. Low efficiency also involve in size of devices which is powered by solar electricity. Low efficient cells need bigger area to convert specific amount of electrical power, and bigger panel means bigger size. It is also means more semiconductor which again increase the cost.

Generally a 150W solar panel size is about  $1 \text{ m}^2$  and can deliver around 1 KW daily. Environmental conditions like intensity of sun radiation, environment temperature and shading always change the output power of a solar panel. Shading is the most destructive factor that can reduce the efficiency. For example, when a small area of panel is located in shading, it's not just that area which is out of service, but that small area can waste the power of an area around 16 times bigger than it, which is under sun irradiation [18]. In this situation a reverse breakdown current can happen in shaded cells junction, cause an internal short circuit and wasting the power by converting it to heat. Therefore, with respect to high sensitivity of the solar panels to shading, it is vital to avoid shading on the panel by putting it in a safe area far from anything that may cause shading on it.

Besides the shading, dust, snow and anything like them can block the sunlight and reduce the output power. Temperature is another factor which has a significant effect



on efficiency of solar panels. The output power is decreasing by increasing in the temperature.

## **1.6 Existing optimizations for photovoltaic technology**

The main focus to develop the photovoltaic technology is on reducing the cost to make in competitive. First it can be achieved by developing the manufacturing technology by concentrating on decreasing the amount of necessary semiconductor, or superseding it by cheaper or more efficient materials, to avoid the destructive effect caused by shading most of panels have bypass diodes between each string of cells or each cell. This can imitated the loss of shading, only to the shaded part of panel. Cooling the panel will also will increase the performance of the panel by reducing temperature. To prevent the dusting problem maintaining and cleaning the panel surface is essential. With a scheduled maintenance program a solar panel can be aged typically 30 years or more.

According to the fact that most of the countries are not on the equator, sun tracker is another option to optimize the performance of a photovoltaic system. Sun tracker or solar harvester; generally improve the sunrise and evening time performance of a solar system [Figure 1-5]. It can increase the total output up to 100%, but it usually used for large systems like solar electric plants greater than 1MW [19]. Sun tracker has better performance in summers, while winter is the season that we hardly need more efficiency in systems, due to shorter daylight.

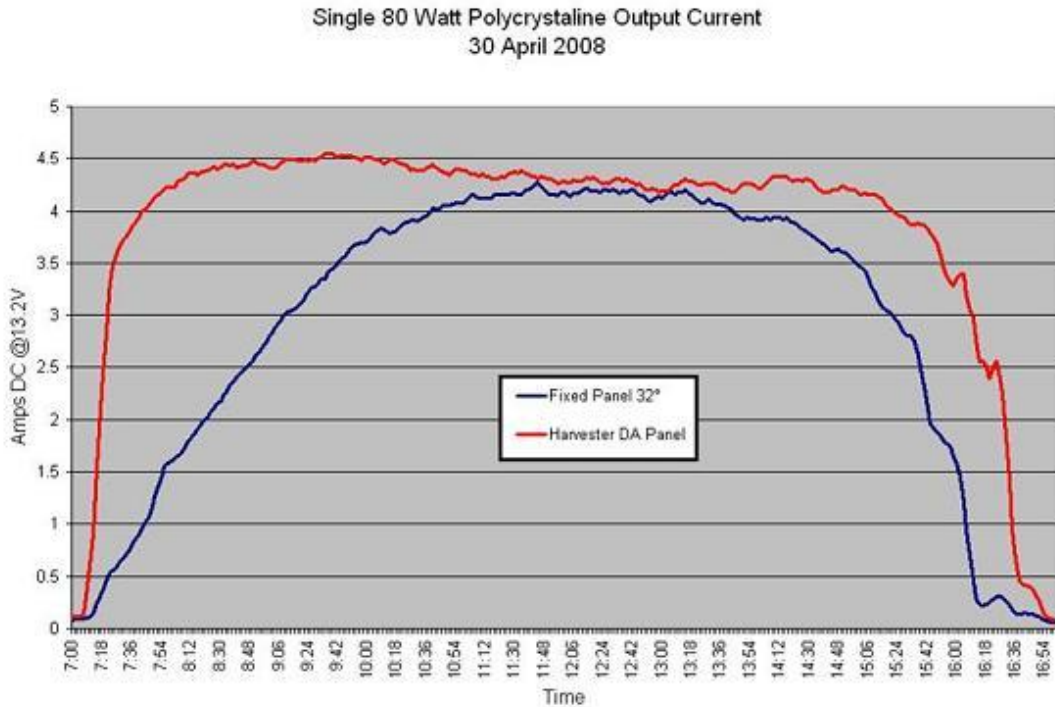


Figure 1-5: Sun tracker performance for an 80 Watt panel

All the discussed problems and given solutions are somehow related to the environmental uncontrolled conditions, but another important factor which has a big effect on solar systems efficiency is related to the connected load.

### 1.7 Load related problems

As discussed earlier, overall efficiency of a solar power system depends on many factors which mentioned before. But there is another electrical related factor which has a big effect of overall efficiency. The load can affects efficiency in many ways.

Some important load related concerns can be listed as below:

- Proper selection
- Using efficient loads
- Startup issue
- Reactive power

Selected loads should meet the system abilities, for instance stand-alone systems cannot support some loads. According to significance of efficiency in solar systems, the required load should be selected carefully in terms of efficiency to reduce the overall power consumption [22]. To prevent from overloading, we should consider the startup problem that may cause by some loads which needs high current for startup. Reactive loads like inductors and capacitors needs reactive power which has to be taken into account [23].

Impedance matching is very important due to maximum power transfer theorem. Any load current change can cause nonlinear changes in voltage and current output of solar panel [4]. To optimize the power efficiency and control these undesired changes a medium used between the solar panel and loads. This medium usually comprises a Maximum Power Point Tracker (MPPT) circuit, voltage regulator, and converter. Referred to Jacobi's law (also known as maximum power transfer theorem), the maximum power will be transfer to load, if the internal resistance of the source is equal to the resistance of the load. This theorem can be extended for AC systems like this: maximum power transfer happened when impedance of the source is equal to complex conjugate of the load impedance. Maximum power point trackers follow this rule to force the system to work in the optimum level [4, 24]. Unlike the sun tracker; MPPT has better performance in winter, because low temperature makes an increment in panel output.

In grid-connected solar systems, The MPPT circuit usually built in the inverters circuits, but in stand-alone systems they usually used to charge batteries so they built in the battery chargers. In fact MPPT is a DC to DC converter which play as an ideal load for the power source to obtain maximum possible power from source and

deliver it to the load (for example battery). In IHSSS project modules power unit has battery storage, and this battery fed the other component of the system. So MPPT is actually an interface between the panel and battery.

## 1.8 Project motivation

Nowadays, growth of renewable energy is very fast, we can see this by looking at the jump of investment on renewable energy from \$ 45 billion in 2005 to \$ 211 billion in 2010. Also looking at the annual PV installed capacity worldwide shows similarly great growth from the 79MWdc in 2005 to 878MWdc in 2010 which leads the total cumulative installed capacity up to 39 GW in 2010 [11]. Figure 1-6 shows the evolution of global cumulative installed capacity during last decade.

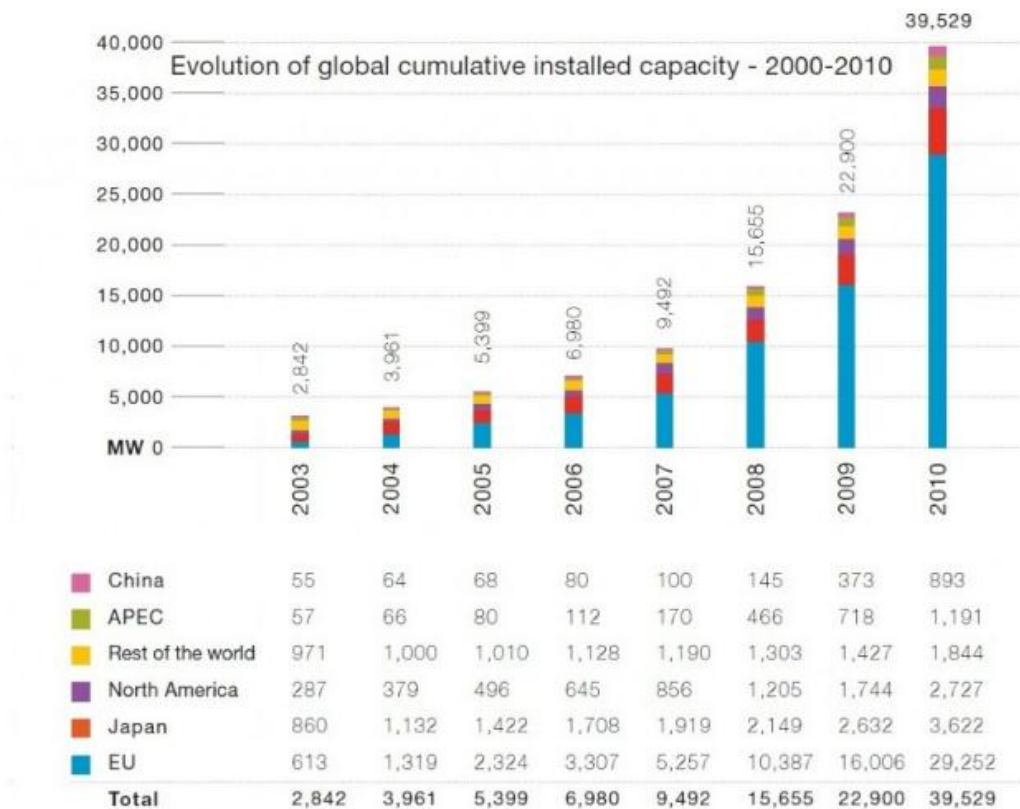


Figure 1-6 : Evolution of global cumulative installed capacity- 2000-2011 [11].

Despite the huge investment and technologic development, the cost of electrical energy produced by solar systems still is not competitive [20]. This motivates us to improve efficiency of solar system not only for IHSSS project but also for any other applications. This study is also motivated by the needs to optimize the energy output of stand-alone solar systems. As discussed before, the efficiency of a solar system is influenced by many factors, so there are many ways to control these factors and consequently there are many solutions for optimization of a solar system.

But improving the efficiency is not always easy, for example increasing the efficiency of the solar cells, needs a very advanced technology and it costs a lot. But improving the methods such as MPPT is not expensive and is much easier. Any progress in optimization of MPPT method can result in better efficiency of the system, and consequently decrement in energy production cost.

## Chapter 2

### Maximum Power Point Tracking

#### 2.1 Role of maximum power point tracking

As mentioned earlier, the cost of installation of solar panel is high and its efficiency is low, according to these facts, optimization in such an expensive system is very important. As discussed before MPPT is one of the most remarkable methods of optimization of solar systems while it is also low cost and easy to implement [25]. However, in simple applications such as calculators where the battery voltage is stable enough to supply the system, use of MPPT is not necessary. As explained before, a photovoltaic panel has an optimal operating point called Maximum Power Point (MPP).

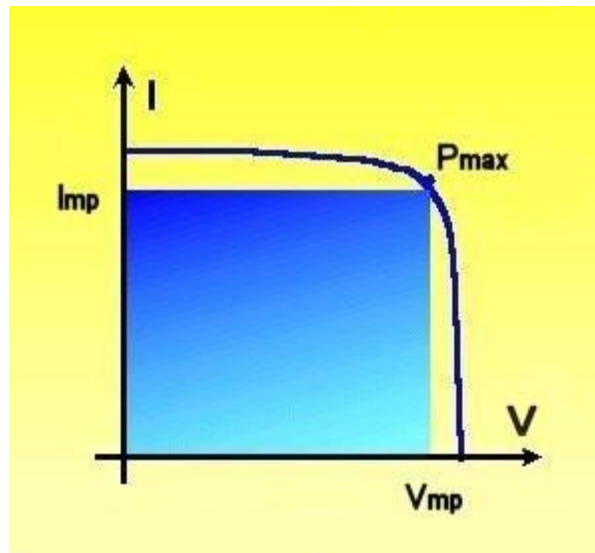


Figure 2-1: Maximum Power Point of a solar panel

The knee of the curve in Figure 2-1 indicates the MPP, MPP of a solar panel also changes with environmental conditions as shown in Figure 2-2.

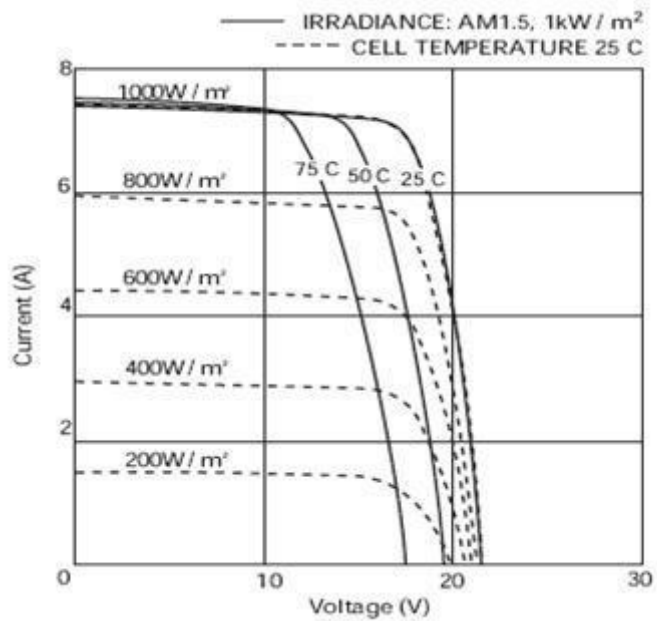


Figure 2-2: I-V curve of solar panel in different environment conditions

Studies show that solar power system equipped with a typical MPPT can deliver 80 to 90 % of their nominal output power, while the solar power system without MPPT can only give 30% of their nominal output power within a long term of time including all varying conditions. To further illustrate this fact, looking at Figure 2-3 we see that a 10% deviation from maximum power point voltage; we lose 25% of power [34].

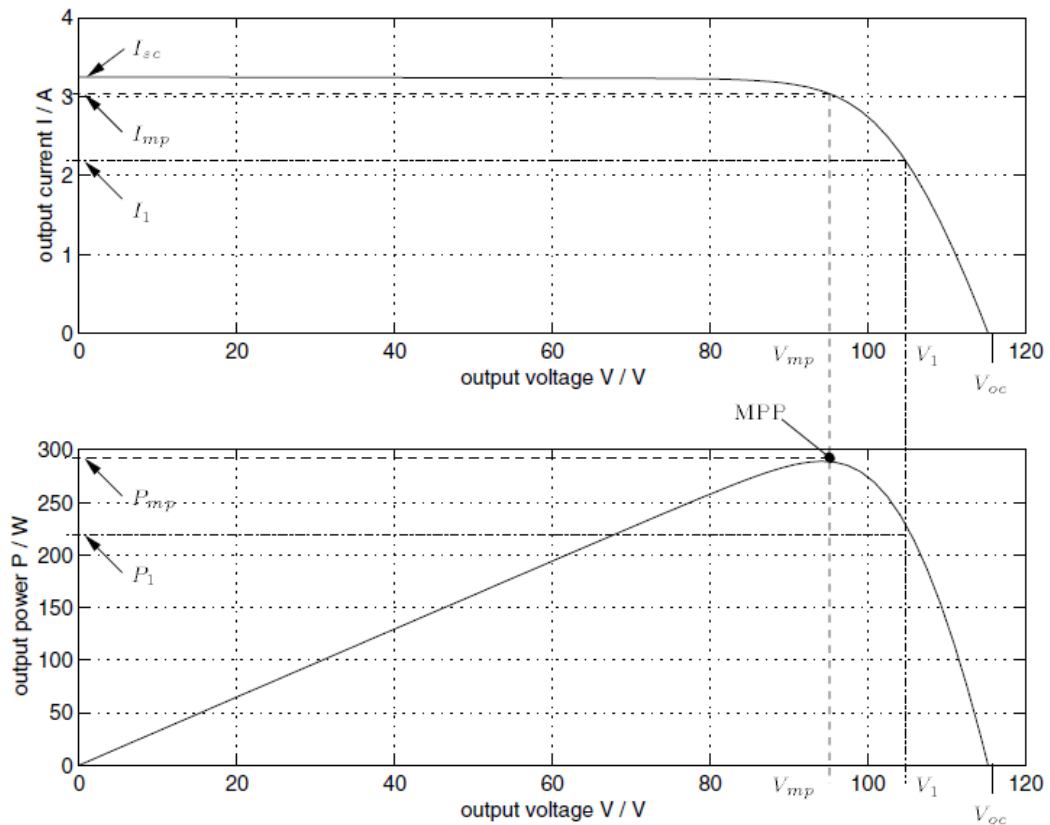


Figure 2-3: P-V and I-V characteristic of a solar array with 168 cells in series operating on STC

## 2.2 Different Techniques

According to what have been discussed, use of an algorithm to monitor the system for tracking its MPP is essential to obtain maximum power. Many methods have been proposed to achieve this aim till now; these methods can be compared according to speed, accuracy, complexity, sensor requirements, cost, and so on [26]. In the following sections some of the most popular algorithms of MPPT are reviewed and classifications in three major groups are presented.

### 2.2.1 Hill Climbing

Hill Climbing is one of the most popular algorithms which are used to track the MPP. This algorithm is the basis for the methods such as INcremental Conductance (INC) and perturbs and observes (P&O). This algorithm forces the system to move



toward the direction which causes an increment in power [27]. Table 2-1 gives a summary of Hill Climbing theory.

In P&O we may get the continuous oscillation around the MPP, therefore some power will be wasted in steady state. In this method we change the panel voltage (increase or decrease), and then observe the change in power, if the change in panel voltage makes an increment in power, it means the operation point is getting close to the MPP, otherwise it means that the direction of change in voltage was wrong.

Table 2-1: Summary of Hill Climbing algorithm [26].

<b>Perturbation</b>	<b>Change in Power</b>	<b>Next Perturbation</b>
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

In Hill climbing change in panel voltage is modified by change in duty cycle of dc converter [26]. As can be seen, there is no definition for steady state condition and it cause an increase in power loss. Solutions have been proposed to overcome this problem but they make the algorithm very slow and this effect on system performance in unstable weather conditions like the cloudy days [28].

The INC method comes to solve this problem by considering the changes in the following formula:

$$\left(\frac{dI_{pv}}{dV_{pv}}\right) + \left(\frac{I_{pv}}{V_{pv}}\right) = 0 \quad (2-1)$$

Equation (2-1) derives from this fact that the slope of P-V or P-I curve for solar panel in MPP is zero. Figure 2-4 shows P-V curves for a solar panel, under two irradiance level of  $S=200\text{W/m}^2$  and  $S=800\text{W/m}^2$ . Top of the curves is the MPP and the slope of the curve is zero:

$$\frac{dP_{pv}}{dV_{pv}} = 0 \quad (2-2)$$

Where  $P_{pv}$  and  $V_{pv}$  are represented panel output power and panel output voltage, respectively. Since:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv} \times I_{pv})}{dV_{pv}} = I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}} = 0 \quad (2-3)$$

(2-3) gives us (2-1), so in MPP (2-1) is also zero and this is where the operating point and MPP are identical which was not considered in P&O algorithm. If the operating point in P-V plan is in the right side of MPP then (2-1) is smaller than zero (negative) and if it is on the left side (2-1) is greater than zero (positive) [24]. Therefore in theory we have a point that the algorithm will be stop on it (when 2-1 is zero) while in P&O operating point is always oscillates around the MPP, actually in real world the (2-1) is never meet the zero due to noise and measurement errors [29]. But in most of applications it is enough that (2-1) be satisfied in a proper threshold [24]. INC is more complicated in software and hardware in compare to P&O, but INC has a better output efficiency [24, 33].

Both methods have problems with fast changes in environment conditions, and in such conditions they don't follow the MPP as shown in Figure 2-4. In Figure 2-4 star

points (\*) represent the MPP for different levels of irradiation between  $S=200\text{W/m}^2$  and  $S=800\text{W/m}^2$ . As you can see MPPT is going another path instead of following stars track (MPP track). Imagine irradiance is changing very fast from  $S=200\text{W/m}^2$  to  $S=800\text{W/m}^2$ . By starting the change, MPPT decrease the voltage to track the MPP, but the system detects an increment in power (due to increase in irradiance level), while operating point is actually going far from MPP. As system detects increment in power, it keeps going to wrong direction and going far from MPP. Despite this problem, both methods are widely used in low budget application according to their simplicity and ease of implementation [24].

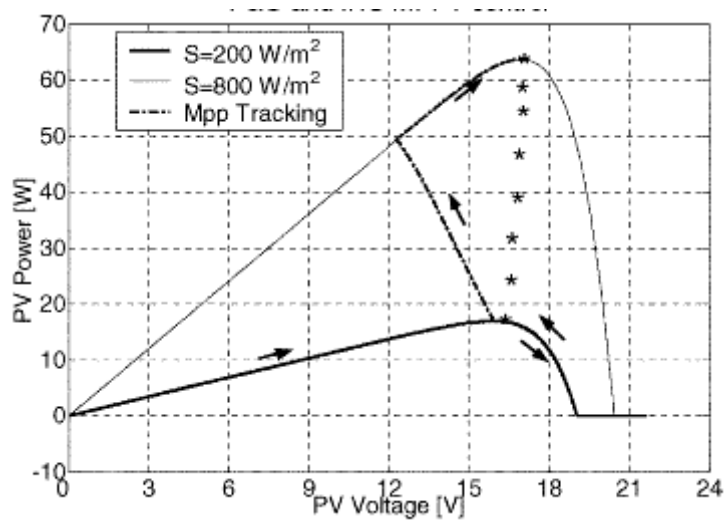


Figure 2-4: MPPT operating point path within the fast irradiation change [24].

### 2.2.2 Fractional methods

In fractional methods we use a constant value to estimate the  $V_{MPP}$  or  $I_{MPP}$  by a ratio of Open-Circuit voltage or Short-Circuit current respectively. In fractional open circuit voltage we have:

$$V_{MPP} \approx k_1 V_{oc} \quad (2-4)$$

Where  $k_1$  is constant related to the panel characteristic and obtained by examining the panel under different irradiation and temperature levels. Usually it has a value between 0.71 and 0.78 [26]. Open circuit voltage should be measured regularly to estimate the MPP voltage, so converter should be switched off regularly and it causes a power loss in the system. In fractional short circuit current we have:

$$I_{MPP} \approx k_2 I_{sc} \quad (2-5)$$

Where again  $k_2$  is a constant value between 0.78 and 0.92 which is used to estimate MPP current via short circuit current. But measuring  $I_{sc}$  is also causes an additional power loss. A switch should be connected to the converter and makes the short circuit for a sensor to measure the short circuit current. Solar lighting systems for street lights usually charge the batteries during daylight and consume the energy at night. Such a system which has no tight limitation for MPPT is a good application for fractional  $V_{oc}$  or  $I_{sc}$  [26].

### 2.2.3 Artificial intelligence methods

Fuzzy logic and neural network have this advantage that they can work by liberal inputs, and they are used in implementing MPPT. Fuzzy logic control has three steps; in the first step, numerical inputs turn to logical inputs. Normally, five logical levels are used for this step, but sometimes for more accuracy seven logical levels may be used [30]. Sometimes the levels are not symmetric because some of them may be more important than others. The inputs are usually error functions which are defined by the user, for example:

$$E(n) = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \quad (2-6)$$

(2-6) is an approximation of (2-2), and when the system is getting close to MPP it goes to zero. Conversion of the inputs is done by a function named membership function and in the second step by look up in a table, named rule base table, the proper decision will be made. At the end it will be converted again to the numerical output. The output is usually a change in duty cycle of power converter [31].

Neural networks also have three steps; input data can be atmospheric information like temperature and irradiance, or electrical parameters like  $I_{sc}$  and  $v_{oc}$ , and the output is usually the duty cycle signal for the converter. In hidden layer every connection between the layer nodes and inputs has their specific weight, and this weight is given by training the system. Actually the accuracy of the algorithm is hardly depending on the training process and training process is depending on the panel characteristic. So for each specific panel we need a special training process. Furthermore the characteristic of a panel can be change by aging, so the training process should be repeated to keep the system updated [32]. Performance of fuzzy logic controllers also depend on their membership function, the rule base table and input error computations, these make the artificial intelligence methods very complex. But MPPT by fuzzy logic and neural network can be very fast and accurate especially in fast atmospheric changes.

There are some other methods that have been omitted here due to their limited application, for example DC-link capacitor droop control is a MPPT system which design for a special connection of solar panel to an AC system. In the other hand some omitted techniques give us the same results that can be obtained by simpler and less expensive techniques.

## **2.3 Selecting the proper technique**

With numerous MPPT techniques, it will be very difficult to decide which technique will be the best choice for a specific solar system; there are many factors which may effect on our selection. Some of the most important concerns will discussed in continue, but still we should decide about the significance of each factors due to their significance in our specific application.

### **2.3.1 Employment**

Simplicity and ease of implement is one of the most important factors which effects on the decision making about the proper MPPT selection for a specific solar power system. Of course this factor is hardly depends on the user knowledge and former experiences. For example a person may be more familiar with analog circuit, and working with analog system is easier for him, while other person may have good knowledge and background of experience about digital circuit. For such a person working with digital system and circuit can be much easier despite the need of programming. But if we don't consider the user knowledge, digital methods are usually more complicated than the analogs, and employing digital methods will be harder than analogs.

### **2.3.2 Budget**

Estimating the cost of implementation of MPPT for a solar power system is not easy at all. And the cost of employing will be clear at the end. But basically digital techniques are more expensive than the analogs one, because digital techniques need to employ microcontrollers and involved by programing. Required sensor for implementation of a MPPT method may affect the total cost of implementation.

### **2.3.3 Sensor requirement**

The number of sensor required for employing a MPPT system can be effect on our choice in selecting suitable method for our application. In some application we can involve with some limitations that don't allow us to use a specific sensor. Voltage measurement is often easier, cheaper, and more precise than current measurement, but some methods need both measurements. Temperature and irradiance sensors rarely used in MPPT applications due to their imprecise measurements [26].

### **2.3.4 Application**

Influence and significance of mentioned factor in choosing proper MPPT method for a system is determined by its application. For instance, consider a solar power system applied in space satellite, in such an expensive application the cost factor is not a concern, and has no effect on our selection, also complexity and ease of implementation; instead accuracy, reliability, and needs for maintenances and tuning are major concerns.

According to the security application of IHSSS project, reliability and efficiency are the two major concerns for us in MPPT method selection. Along with what Saied before, Hill climbing methods are the best choice for such a security applications. The space applications are also use Hill climbing algorithm for MPPT. A compression table is given for more information [Table 2-2].

Table 2-2: Comparison of different MPPT techniques[26].

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



## Chapter 3

### Modelling the Solar Power System

In this chapter a solar power system will be modelled with an aim to simulate the behaviour of the system in various operating conditions to study the proposed MPPT system. The power source for the IHSSS project includes a solar panel and battery storage as a buffer between the load and the source. There is also a DC-DC converter used for matching between the panel and battery as shown in Figure 3-1. In this converter, the ratio of conversion is always adjusted by a control system to achieve the best operating point which must be as close as possible to the maximum power point. This control system which is normally designed to be inside of the converter is the MPPT. In this chapter we introduce and model all the components so that we can simulate the entire system.

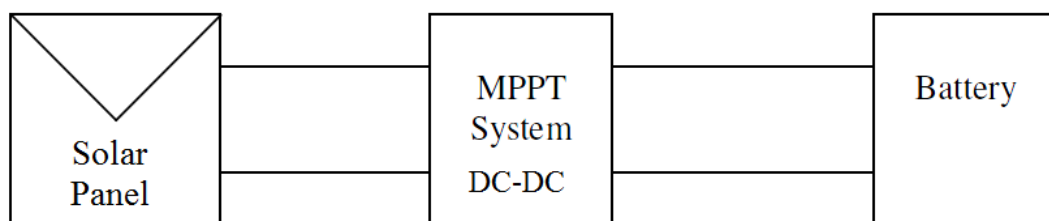


Figure 3-1: Block diagram of the solar power unit

#### 3.1 Modelling of a Solar cell

In this section we will review and investigate some proposed model of a solar cell. Solar cell is a semiconductor which absorbs light and converts it to electrical energy, and as discussed before. Most of the solar cells are made of silicon. So, a p-n

junction can be considered as a solar cell. When this junction is exposed to light irradiance, a voltage is produced on its terminals. This voltage is called photo-voltage, and if the terminals are connected to a load, there will be a current passing through the terminals into the load which is called photo-current [35]. This behaviour of a solar cell can be modelled as shown in the circuit of Figure 3-2. This is the simplest model for a solar cell. The mathematical model for this circuit can be written with the help of Shockley Diode model equation as given below [36]:

$$I_{pv} = I_{ph} - I_s \left[ e^{\frac{qv}{nKT}} - 1 \right] \quad (3-1)$$

The equation (3-1) describes the output current of a solar cell ( $I_{pv}$ ), in terms of voltage across the diode  $V$ , diode reverse saturation current  $I_s$ , photo-current generated by the cell and the junction temperature  $T$  in Kelvin. Also,  $q$  is the electron charge ( $1.602 \times 10^{-19}$  C),  $K$  is the Boltzmann's constant ( $1.381 \times 10^{-23}$  J/K) and  $n$  is the diode ideality factor. We can see from equation (3-1) that a solar cell has an exponential relation between the current and voltage.

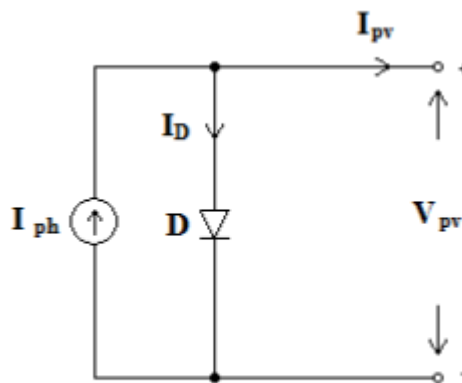


Figure 3-2: A simple model for solar cell [40].

This equation is very similar to the regular diode equation. Actually the behaviour of the solar cell is also very similar to the regular diode in darkness. But unlike a normal diode, if the solar cell is illuminated, an open circuit voltage appears which leads to a short circuit current  $I_{sc}$  visible as a current offset in I-V characteristic curve of the solar cell as shown in Figure 3-3.

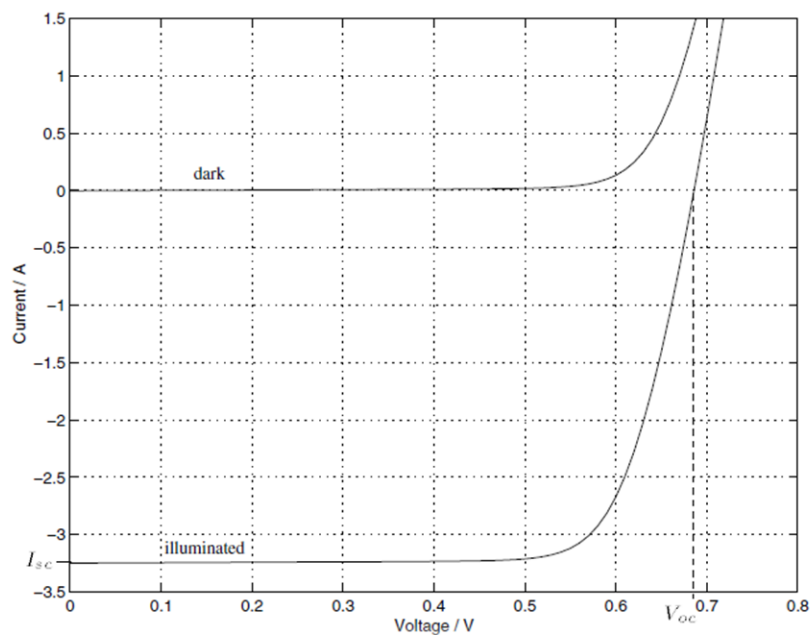


Figure 3-3: The I-V characteristic of a solar cell

Actual measurements on real solar cells in different operating conditions show that this model is not very accurate. We can increase the accuracy of the model by adding the following factors to the model:

- Dependency of the reverse saturation current on the temperature
- Dependency of the photo- current on the temperature
- Adding a series resistance to represent the internal resistance of the cell
- Considering the diode ideality factor as a variable

- Adding a parallel resistance to model the leakage current of diode

Considering an internal resistance for the solar cell and adding it to the model gives us a more precise result. To model internal resistance and leakage current of diode and to make the model more accurate we can add two resistances,  $R_{se}$  and  $R_{sh}$  into the output of the model shown in Figure 3-4.

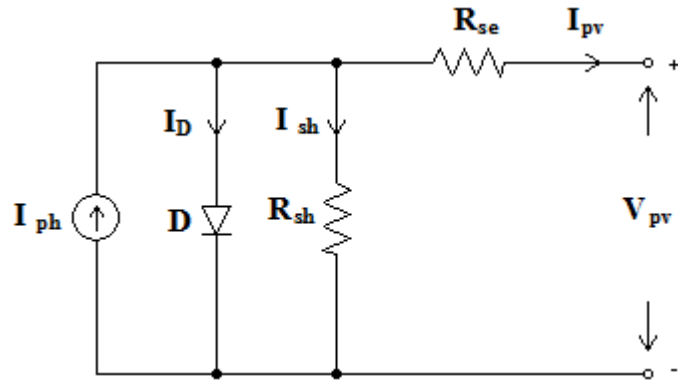


Figure 3-4: Equivalent model of solar cell with internal resistance [40].

This equivalent circuit gives us this new mathematical model:

$$I_{pv} = I_{ph} - I_s \left[ e^{\frac{q(v_{pv} + I_{pv}R_{se})}{nKT}} - 1 \right] - \frac{v_{pv} + I_{pv}R_{se}}{R_{sh}} \quad (3-2)$$

Where  $I_{pv}$  and  $V_{pv}$  are the solar cell output current and voltage respectively,  $I_{ph}$  is photo-current generated by the cell,  $I_s$  is the reverse saturation current of the diode,  $n$  is the diode ideality factor,  $T$  is the temperature in Kelvin, and  $q$  and  $K$  are the electron charge and Boltzmann constant, respectively. Photo-current can be obtained by the following equation:

$$I_{ph} = S \times I_{ph(max)} \quad (3-3)$$

Where  $S$  is the sun irradiance level in percentage and  $I_{ph(max)}$  is the photo-current generated by a solar cell in a standard testing condition [37]. This equation shows the dependency of cell characteristic to the irradiance. Dependency of the photo-current and reverse saturation current on the temperature will be described later in Chapter 4.

Estimating the diode ideality factor is the next challenge in making a good model. The diode ideality factor ( $n$ ) has also a significant impact on the calculated result. This factor is highly depended on the material and manufacturing process and it can vary with the operation conditions. The diode ideality factor is changing between 1 and 2 for silicon made solar cells, and it depends on the quality of the material. A recommendation states that ( $n$ ) falling close to the 1 in high currents, and getting near 2, in high currents [38].

To simulate this variable factor another model has been introduced as shown in Figure 3-5, which includes two diodes parallel to photo-current source instead of one. Each diode has its independent reverse saturation current. One diode has an ideality factor equal to one and the other one has an ideality factor equal to two [39].

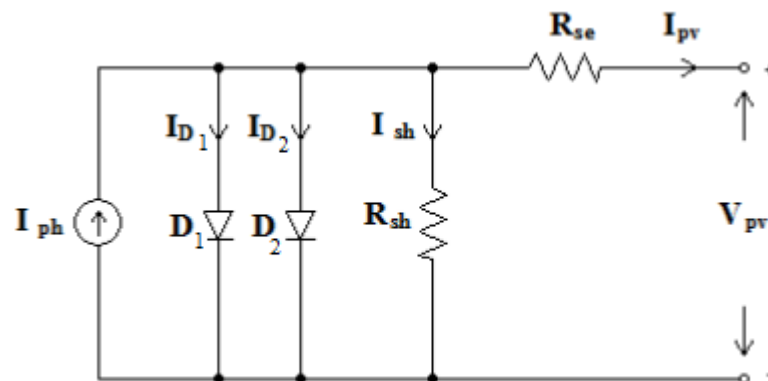


Figure 3-5: The equivalent circuit of double diode solar cell model [40].

Equation (3-4) describes the I-V characteristic of the new double-diode model:

$$I_{pv} = I_{ph} - I_{s1} \left[ e^{\frac{(v_{pv} + I_{pv} R_{se})}{n_1 V_t}} - 1 \right] - I_{s2} \left[ e^{\frac{(v_{pv} + I_{pv} R_{se})}{n_2 V_t}} - 1 \right] - \frac{v_{pv} + I_{pv} R_{se}}{R_{sh}} \quad (3-4)$$

Where  $V_t$  is the thermal voltage:

$$V_t = \frac{KT}{q} \quad (3-5)$$

Despite that the double-diode model has more accuracy; it is usually preferred to use a single diode model in most of the simulations [41 - 44]. This is because of the fact that it cannot improve the accuracy of the model as much as it increases the complexity. It is completely useless as we complicate the model used when we can obtain almost the same result with a simpler model.

### 3.2 Modelling of Solar panel

Solar cells are usually connected in series to make a solar panel. Equation (3.2) is re-written as below for a panel consisting of  $z$  cells:

$$I_{pv} = I_{ph} - I_s \left[ e^{\frac{q(v_{pv} + I_{pv} z R_{se})}{znKT}} - 1 \right] - \frac{v_{pv} + I_{pv} z R_{se}}{z R_{sh}} \quad (3-6)$$

These panels can be connected either in series or parallel to support any desired voltage and current. Figure 3-6 and Figure 3-7 show the amount of dependency of the I-V and P-V curves of a solar cell to the temperature and irradiance respectively.

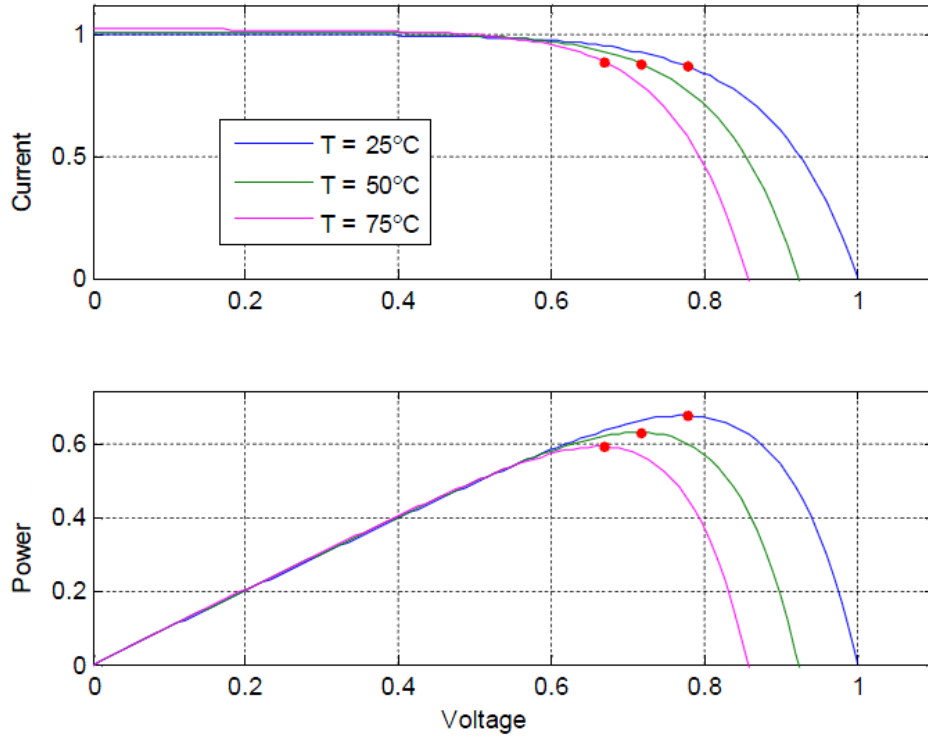


Figure 3-6: V-I and V-P curves at constant irradiation ( $1 \text{ kW/m}^2$ ) and three different temperatures.

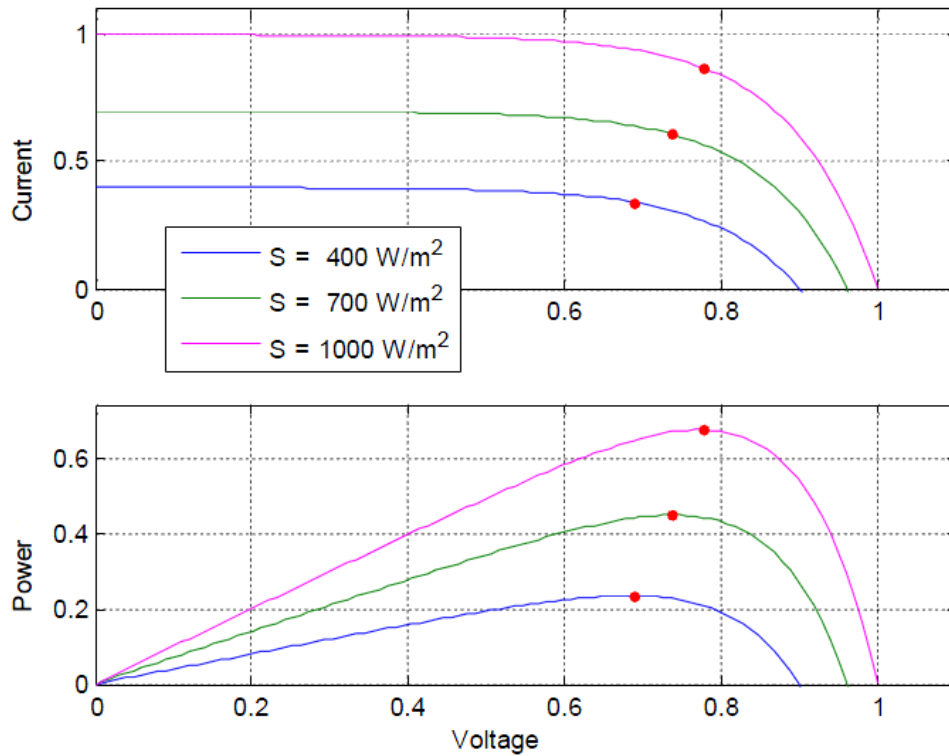


Figure 3-7: V-I and V-P curves at constant temperature (25°C) and three different Irradiance level.

We can see from Figure 3-6 that a change in temperature makes a considerable change in the output voltage of the cell, but does not have the same strong effect on the output current of the cell. The change in insolation level has a big effect on the output current of the cell, while the output voltage of the cell does not change so much as shown in Figure 3-7. Looking at the P-V curves in Figure 3-6 and Figure 3-7 also shows that the change in insolation level has a greater impact on the output power of the cell in comparison to changes in temperature. So, irradiance factor is more significant than temperature factor.

From the P-I curves, it's obvious that the output power is not only depended on temperature and insolation, but also it depends on the operating point voltage. We saw this sensitivity before in Figure 2-3.



So, it is very important to force the system to work with voltages as close to the MPP voltage as possible, and as we have said before this is the MPPT job. The dependency of the V-I and therefore P-I characteristic of the solar panel to the temperature and insolation level, the MPP voltage  $V_{mpp}$  will consequently change by the atmospheric conditions.

### **3.3 Modelling of DC-DC converter**

A DC-DC converter is a Switching Mode Power Supply (SMPS) used as an interface between the load and source. The buck converter has been selected for our project application because the battery voltage used in the project is 12 V. This value is enough to support all the components of the IHSSS project, while the solar panel can produce a greater voltage, in most of the operating conditions. So, a step down converter will be a good solution for converting the output voltage of the panel to a voltage that we need to charge the battery. The conversion ratio can be adjusted by the duty cycle of switching signal. A switching power conversion usually consists of a switch, capacitor and an inductor, and these blocks are all represented in the Simulink program. Switching converters are very efficient as ideally they consume little power.

As the Simulink program has the ability of modelling all the elements of a DC-DC converter, we don't need mathematical models of these components for simulation.

### **3.4 Modelling of MPPT**

We have seen earlier that the conversion ratio of the converter can be adjusted by duty cycle of switching. The MPPT control circuit guides the operating point to the

maximum power point, by adjusting the duty cycle of the switching device of the converter. We choose the Hill climbing algorithm for applying MPPT. Figure 3-8 shows the flowchart of a Simple Hill Climbing algorithm.

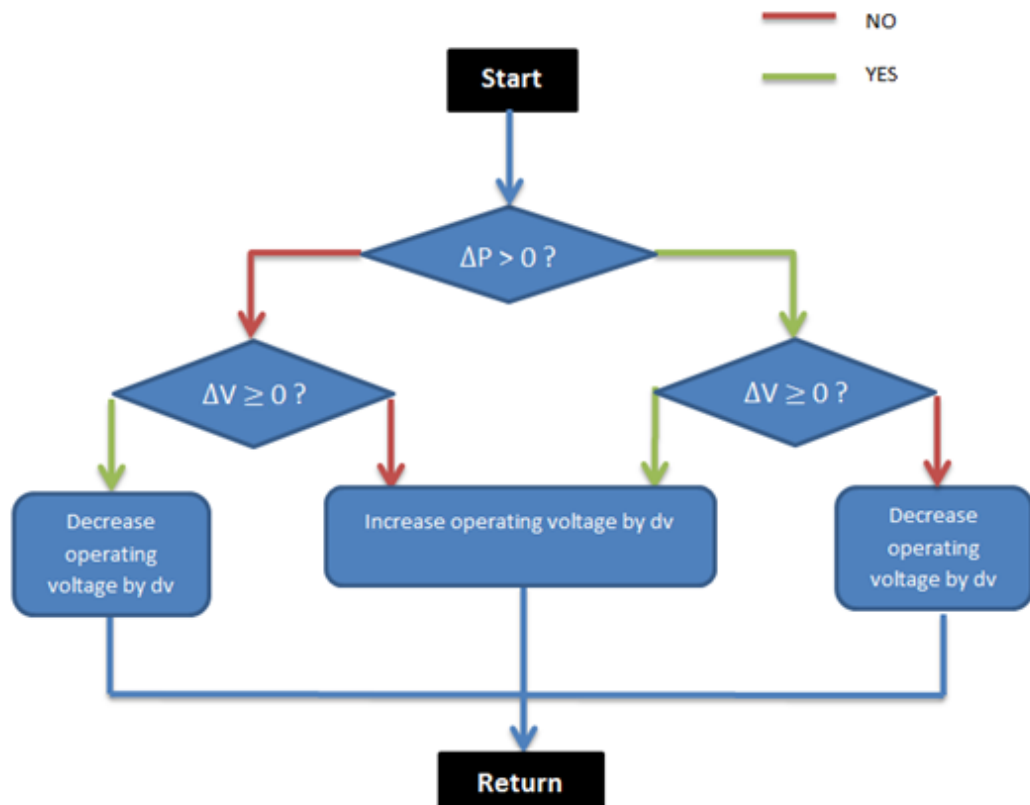


Figure 3-8: Flowchart of Simple Hill Climbing method

As explained earlier, Hill climbing method starts with a change in operating voltage and then it observes the changes in power to correct the change in voltage. In simple Hill climbing algorithm four conditions have been defined, but there are only two operations for these four conditions. The solutions are increment or decrement in voltage with a constant rate. Figure 3-9 shows the Improved Hill climbing algorithm.

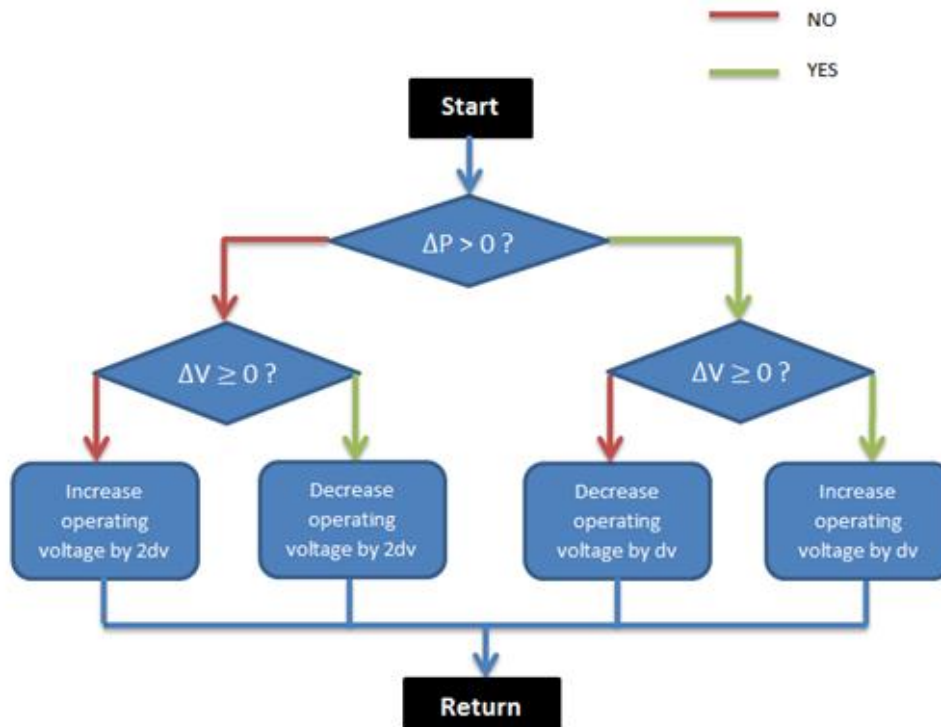


Figure 3-9: Flowchart of Improved Hill Climbing method

As we can see from the flowchart, we define four conditions for changing voltage and power and there are also four solutions for these situations. If the power is decreased by an increase in operating voltage, the system will compensate this wrong change with a decrease in the operating voltage by a rate two times of the first change rate. If this power reduction is caused by a decrease in the operating voltage, the system will increase the voltage again by a rate two times of the first change rate to compensate for the false operation. If the change in voltage has caused an increment in power, the system keeps applying the same change with the same rate. The MPPT system will apply all the changes by making a change in the duty cycle of the switching converter, this approach will be explained in the next chapter.

## Chapter 4

### SIMULATION

Simulation is required to estimate the performance of a system under different conditions. The Matlab software has a simulation tool, named Simulink which is used to evaluate different components/variables of the solar power system that was modelled in the previous chapter. In Simulink we can model all the components and test them under different conditions without any limitation.

#### 4.1 Matlab model of solar panel

In Chapter 3, we have introduced several models for simulating the behaviour of the solar panel; the proposed models had different degrees of accuracy and complexity. For our simulations we choose the following simplified single-diode model for a single pv cell:

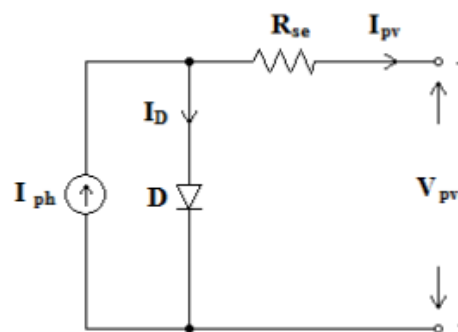


Figure 4-1: Simplified single-diode model of solar cell

The chosen model has a good accuracy for simulation process despite its simple configuration. As explained earlier the single diode model is preferred to the double diode model in most of simulations because the effect of parallel resistance which corresponds to the leakage current is very small. This has been neglected in the selected model ( $R_{sh}$  is assumed to be infinite).

## 4.2 Calculation of the model parameters

DS-A1-40 solar module is selected for our simulations and all the parameters have been extracted from the manufacturer data sheet for this module. The module specifications are given in appendix B. We saw in equation (3-3) that  $I_{ph}$  is directly related to the insolation level. When the solar cell is short circuited a negligible current passes through the diode and  $I_{ph(max)}$  is equal to the  $I_{sc}$  [44,45], in STC where  $S$  is 1 and temperature is 25°C, nominal photo-current is equal to the nominal short circuit current which is equal to 2.57A for AS-A1-40 module.

Dependency of the photo-current to the temperature can be explained by this formula:

$$I_{ph} = I_{ph(T_0)} \times [1 + X_a(T - T_0)] \quad (4-1)$$

Where  $X_a$  is:

$$X_a = \frac{I_{sc(T_1)} - I_{sc(T_0)}}{I_{sc(T_0)}(T_1 - T_0)} \quad (4-2)$$

The reverse saturation current at 25°C can be derived from the short circuit current and the open circuit voltage at this temperature:

$$I_{S(T_0)} = \frac{I_{sc(T_0)}}{(e^{\frac{qV_{oc(T_0)}}{nKT_0}} - 1)} \quad (4-3)$$

Where  $T_0 = 273 + 25$  is the temperature in Kelvins. The relation between  $I_s$  and temperature is complicated:

$$I_s = I_{S(T_0)} \times \left(\frac{T}{T_0}\right)^{\frac{3}{n}} \times e^{\frac{-qE_g}{nK\left(\frac{1}{T} - \frac{1}{T_0}\right)}} \quad (4-4)$$

Where  $E_g$  is the band gap energy in electron volt which is chosen as 1.7 for DS-A1-40 polycrystalline solar cell. An increase in temperature will cause an increase in  $I_s$  (4-4), and it will also cause a decrease in open circuit voltage  $V_{oc}$ . As mentioned earlier adding dependency of the reverse saturation current on the temperature will increase the model's accuracy.

The diode ideality factor ( $n$ ) varies between 1 and 2 during different operating conditions; Figure 4-2 shows the impact of changing this factor on Matlab model V-I curve. For the best curve matching result, we choose 1.97 for diode ideality factor.

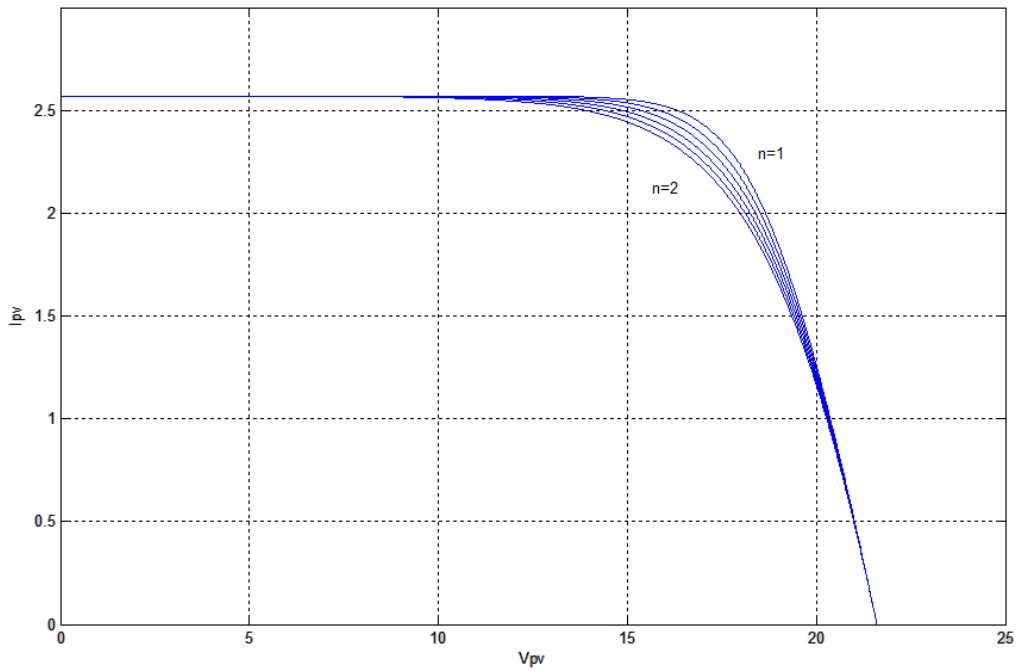


Figure 4-2: Matlab model I-V curves for different ideality factors

The series resistance  $R_s$  has a notable effect on the I-V curve slope around the open circuit voltage point as shown in Figure 4-3.

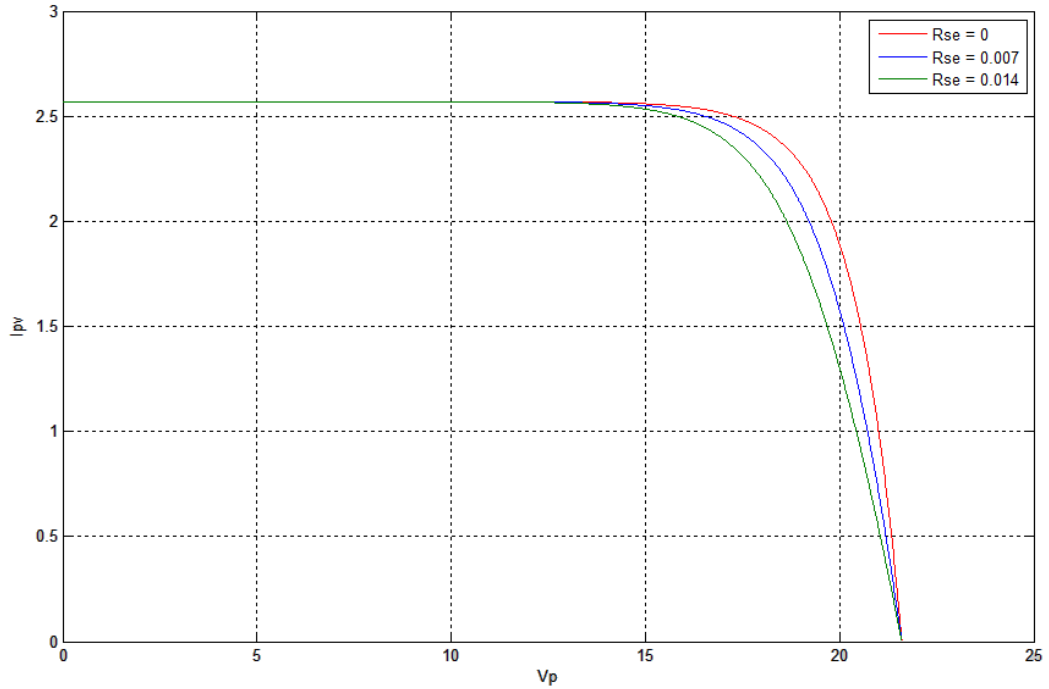


Figure 4-3: Matlab model I-V curves for different series resistances

This resistance represents the internal resistance of the cells and interconnections of the panel.  $R_s$  can be obtained either by choosing the best value from Figure 4-2 to match the manufacture curve, or can be calculated by the next formula which has been obtained by taking the derivative of equation (4-3) and rearranging based on  $R_s$  for  $V=V_{oc}$  [38]:

$$R_s = \frac{-dV}{dI}(V_{oc}) - \frac{1}{X_b} \quad (4-5)$$

Where  $X_b$  is:

$$X_b = I_{s(T_0)} \times \frac{q}{nKT_0} \times e^{\frac{qV_{oc}(T_0)}{nKT_0}} \quad (4-6)$$

The Matlab code which represents this model is given in appendix A.



The equation which describes the output current of solar panel is an iterative equation. To solve this equation in Matlab, Newton-Raphson method used as a numerical method. With five step of iteration, it can converge to the answer with a good approximation.

### 4.3 Simulink Implementation

In the last section we implemented the solar panel with Matlab codes, as we want to implement the other parts of the system in Simulink, those Matlab codes can be used in Simulink as an Embedded Matlab function block, in order to easily connect to the other parts of the system. Figure 4-4 shows the Simulink model of the solar panel. We can easily implement the other parts by using the Simulink library blocks. Figure 4-5 shows the implementation of Buck converter in Simulink.

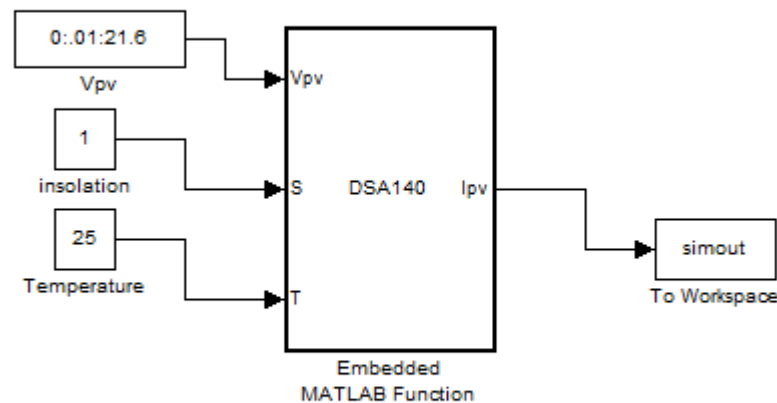


Figure 4-4: Simulink model of DS-A1-40 solar panel

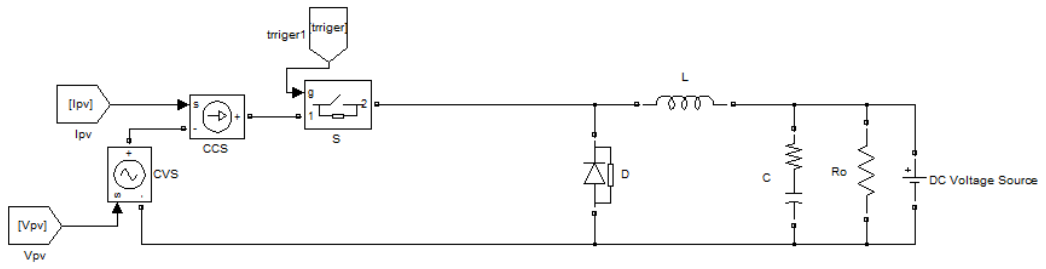


Figure 4-5: Simulink implementation of Buck converter

As can be seen in Figure 4-5, Buck converter circuit is connected to a DC voltage source; this DC voltage source represents our battery storage device that plays the role of a load here. As we design the 12V battery storage for the IHSSS power system, we can use a 12V DC voltage source to model the battery storage.  $I_{pv}$  and  $V_{pv}$  inputs come straight from the solar panel, another input is a trigger signal which is applied to the switch, and this trigger signal comes from the MPPT system to control the duty cycle of the converter. In Chapter 3, we mentioned that MPPT system can adjust the operating point of the solar panel by varying the duty cycle of the converter, but how does it work?

To answer this question, first we should know about the Buck converter. In a Buck converter the voltage conversion ratio can be adjusted by switching status. During operation time, switch will be On and goes Off with constant frequency  $f_s$ . The ratio of the time that switch is On  $T_{on}$  to period time  $T_s$  is duty cycle  $D$  (4-8).

$$T_s = \frac{1}{f_s} \quad (4-7)$$

$$D = \frac{T_{on}}{T_s} \quad (4-8)$$

Conversion ratio is also defined by the duty cycle:

$$V_{out} = V_{in} \times D \quad (4-9)$$

As the output of converter is connected to a constant DC voltage source, any change in the duty cycle, will make a change in the input voltage  $V_{in}$ , which is in fact, the operating voltage of the solar panel.

Figure 4-6 and Figure 4-7 show the Simulink implementation of Simple Hill Climbing and Improved Hill Climbing algorithms respectively. As can be seen from Figure 4-6 and Figure 4-7,  $V_{pv}$  and  $I_{pv}$  as inputs of the MPPT are fed into a sampling subsystem and this subsystem calculates Delta V and Delta P for the next level which decides about how to make a change in the operating voltage. The decision also goes to another subsystem for conversion into a trigger signal for the switch.

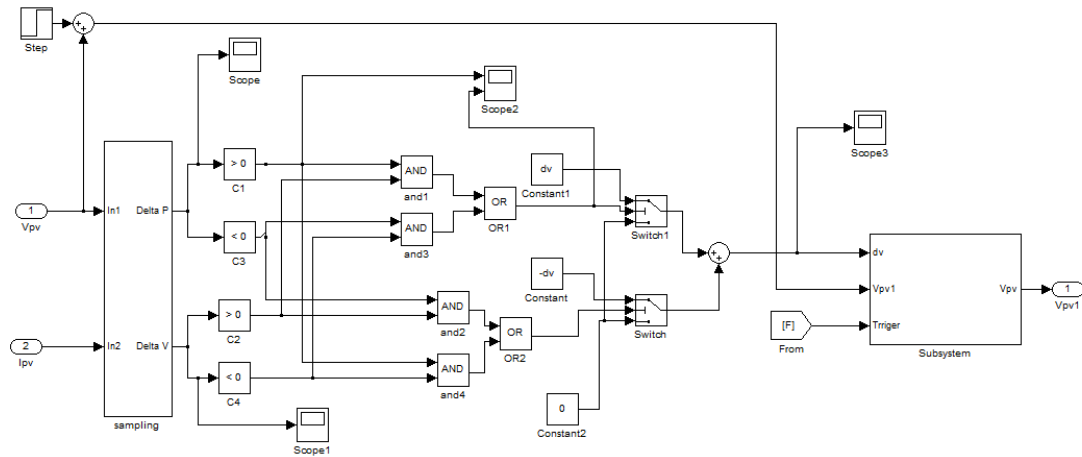


Figure 4-6: Simulink implementation of Simple Hill climbing algorithm

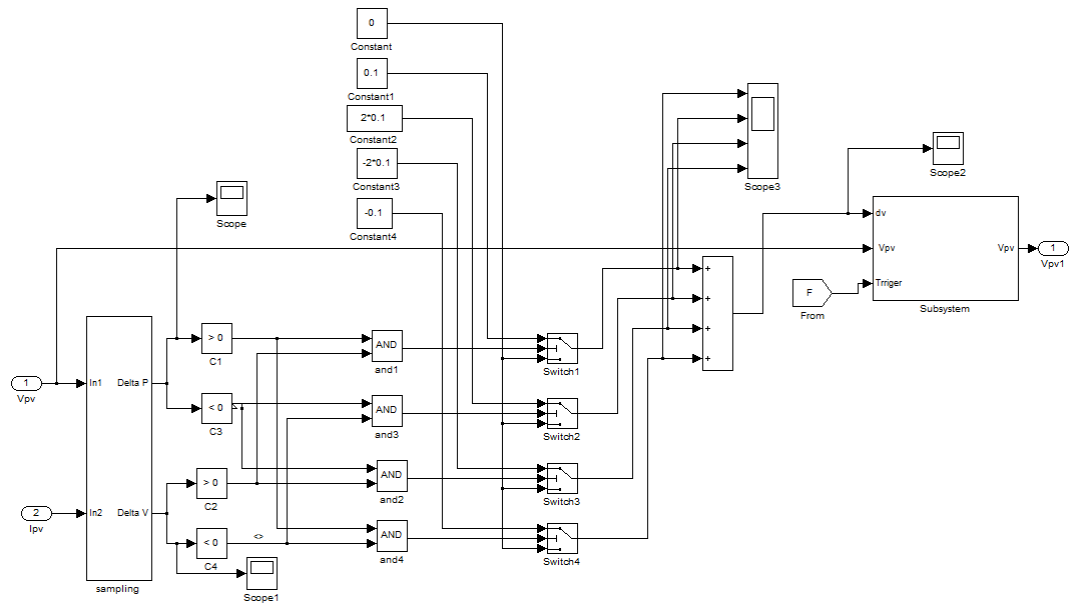


Figure 4-7: Simulink implementation of Improved Hill climbing algorithm

Figure 4-8 shows the sampling subsystem in detail. As shown in this figure,  $I_{pv}$  and  $V_{pv}$  are the two inputs of the system used to calculate delta V and delta P.

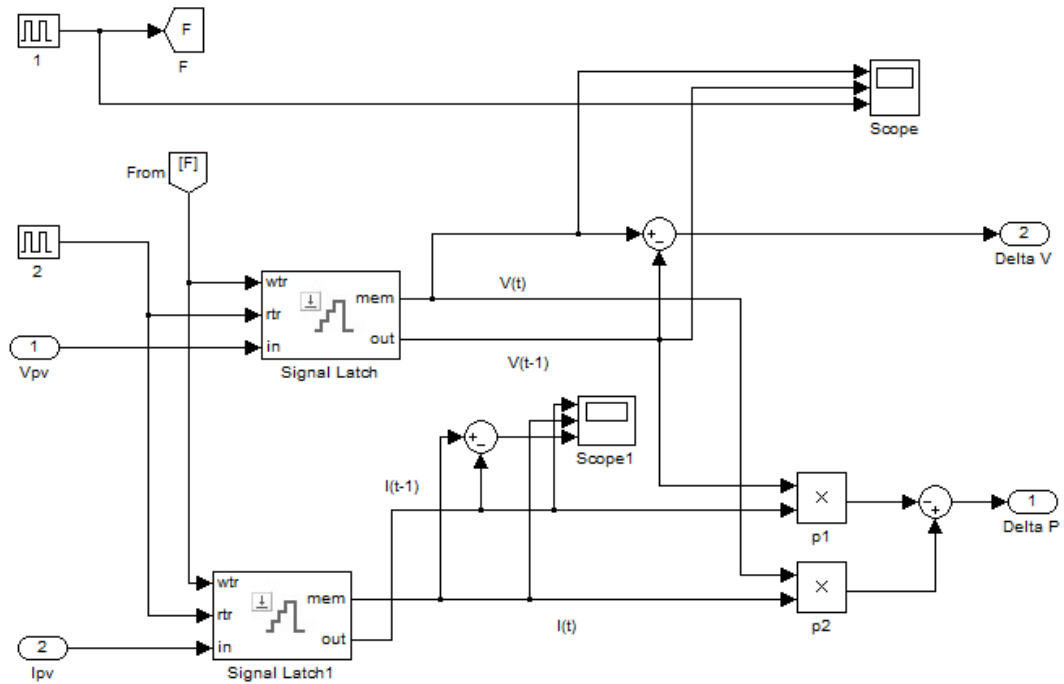


Figure 4-8: Simulink model of sampling subsystem of Hill Climbing MPPT

#### 4.4 Simulation of MPPT System

In the last section we implemented all the components of the system one by one and now we can connect all these parts together to simulate the whole system performance under different conditions. Figure 4-9 illustrates the complete implemented system.

All the simulations run in a computer with core i3 CPU 2.1 GHz and 2 GB installed memory.

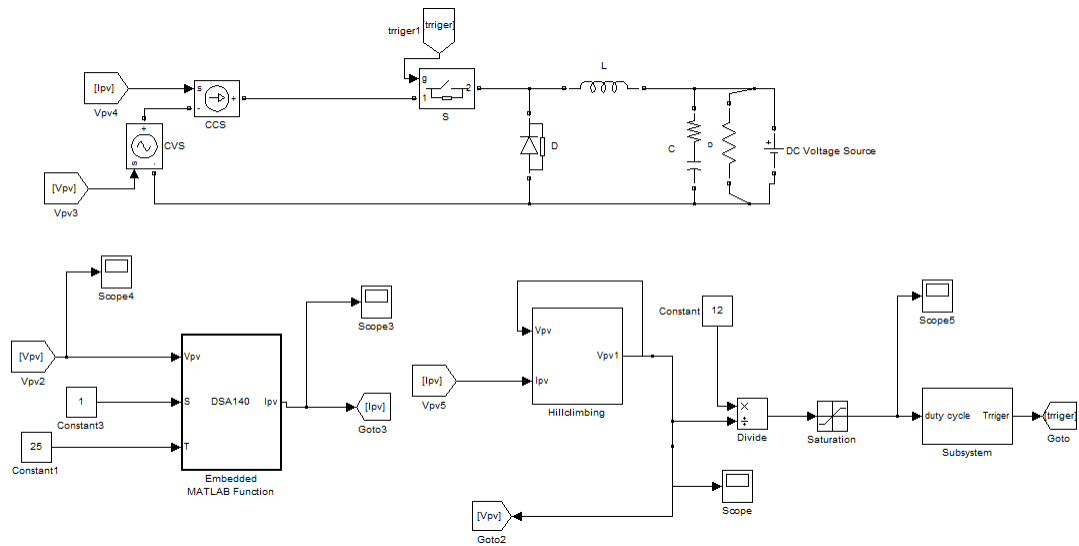


Figure 4-9: Simulink Implementation of whole solar power system

To evaluate and compare the performance of the improved Hill climbing MPPT with the ordinary Hill Climbing MPPT, we define three conditions for simulation. We will examine the system under changing insolation, changing temperature, and stable conditions.

#### 4.4.1 Testing the system under stable conditions

In this part of simulation the system will be tested under constant irradiance level and constant temperature. In such a situation we can't evaluate performance of MPPT, but our focus is on the output power ripple which mainly caused by an oscillation around the MPP. This oscillation also depends on the sampling frequency. In this simulation temperature set to 25°C and insolation set to 1 sun (STC).

We know that whenever the MPP changes the MPPT will adjust the duty cycle in order to avoid the system to deviate from the MPP. Figure 4-10 and Figure 4-11 show the simple Hill climbing and improved Hill climbing MPPT performances under constant condition respectively. As shown in the figures, we have oscillation in

both systems around the MPP, and this oscillation is caused by the continuous perturbation of the system to find the MPP which is already discussed in 2.2.1.

Looking at the duty cycle, it shows how the system changes the signal directions whenever a decrement in power is detected. Sampling frequency set to 100Hz in both MPPT systems. Sampling time should be longer than the system response, otherwise the system can not respond to changes to make a correction and it can not track the MPP. Assume that a power decrement is detected by the MPPT, to respond to this decrement system will change the direction of voltage. If the sampling time was too short MPPT again will detect a decrement in power, because the system did not have the sufficient time to respond to the former change, and to respond to this decrement, MPPT will change the voltage direction again.

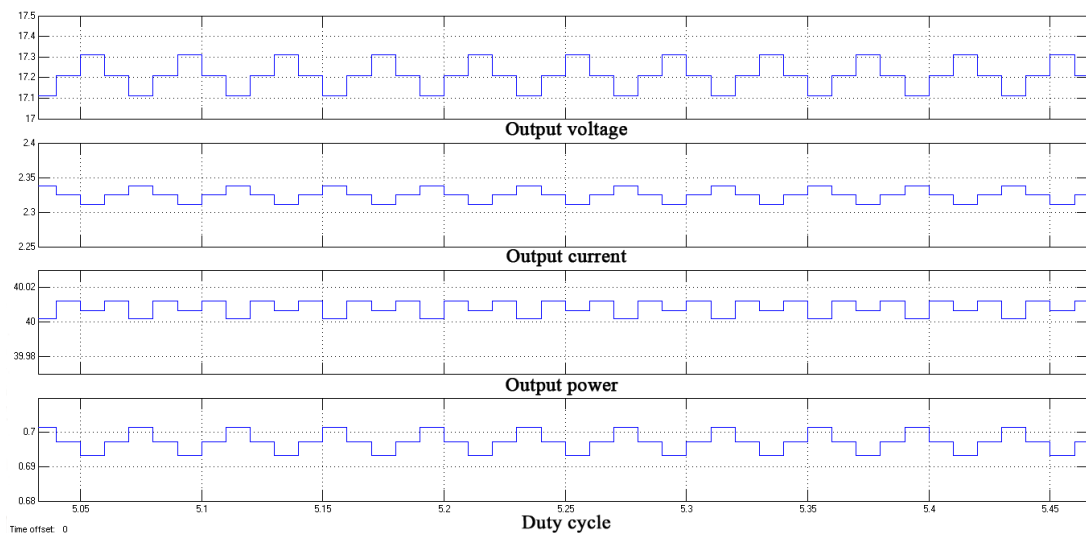


Figure 4-10: Voltage, Current, Power and Duty ratio of Simple system under stable condition.

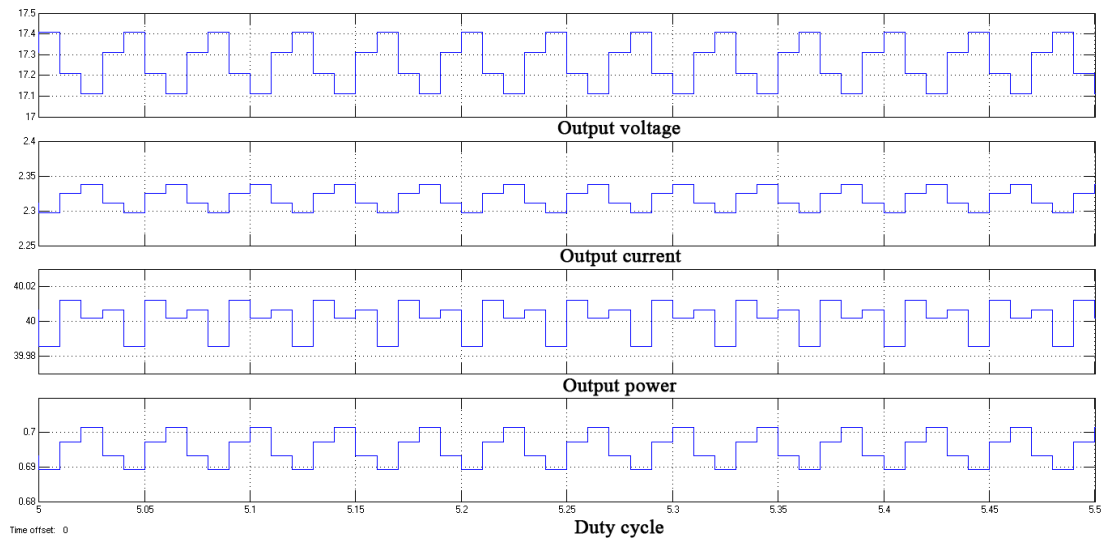


Figure 4-11: Voltage, Current, Power and Duty ratio of Improved system under stable condition

A comparison between these two figures show, in constant conditions we have less oscillation in simple Hill climbing MPPT, and this can be described by greater changing rate in Improved Hill climbing MPPT technique.

#### 4.4.2 Testing the system under changing insolation condition

To monitor the system performance under changing insolation condition, we applied a signal to insolation input (S) instead of a constant value one, but temperature is still 25°C. The signal has 0.5 amplitude and from  $t = 2$  sec insolation will increase rapidly to 1 during 0.25 seconds ( $t = 2.25$  sec), and after that it stays unchanged. Simulation runs for 10 seconds. Figure 4-12 and Figure 4-13 show the simple Hill climbing and improved Hill climbing MPPT performances under changing insolation condition respectively.



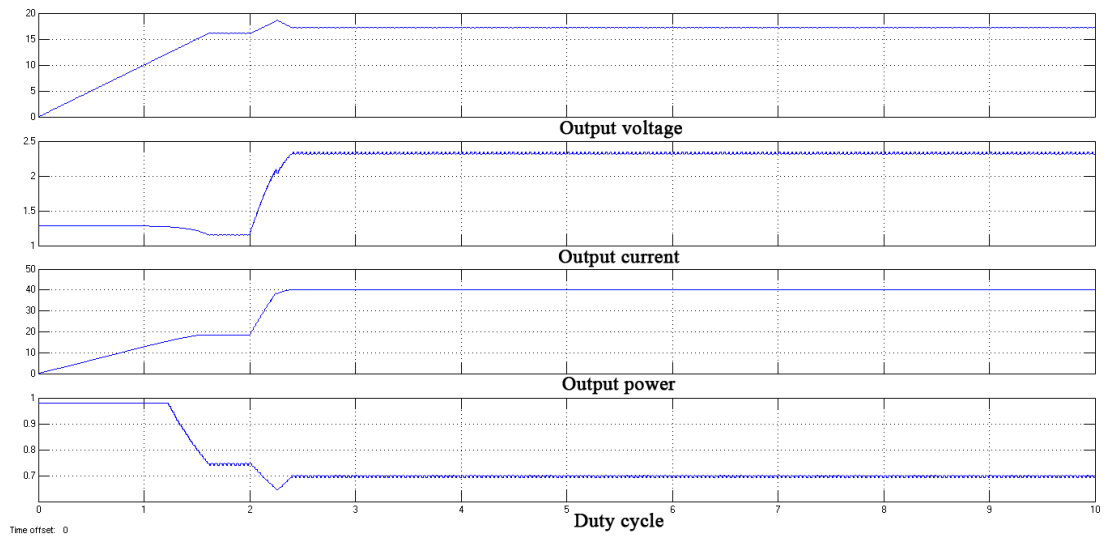


Figure 4-12: Voltage, Current, Power and Duty ratio of Simple system under changing insolation condition

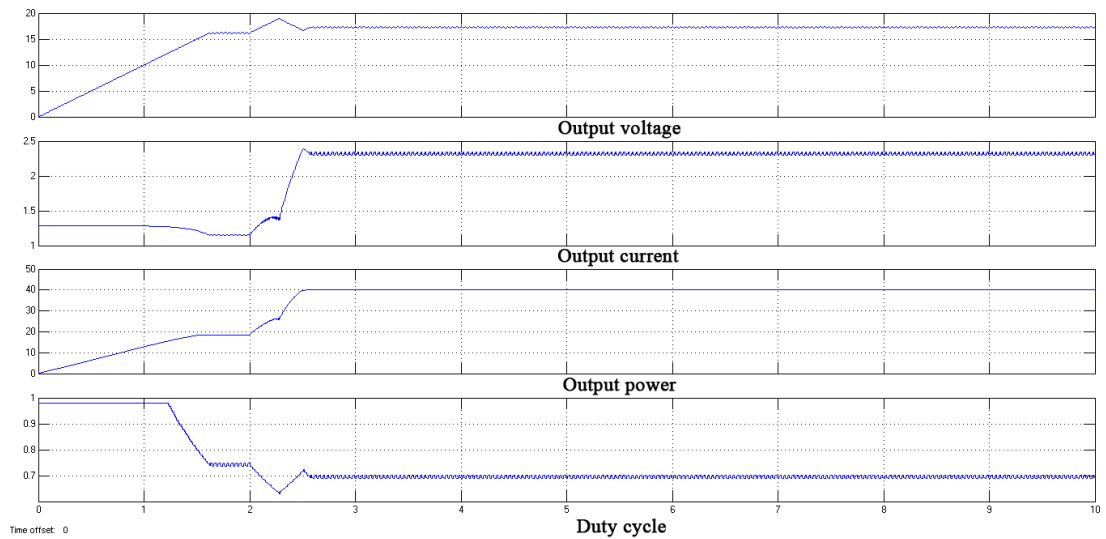


Figure 4-13: Voltage, Current, Power and Duty ratio of improved system under changing insolation condition

The performance of the two systems is very similar in this condition and we can't see any remarkable difference between them. At the beginning of the simulation, voltage of solar panel increased rapidly, because it was set to zero and initial value for insolation was set to 0.5 sun. Increase in insolation happened very fast (during 0.25

seconds), and this very fast change is far from real world changes. But if a system can tolerate such a fast change, and still track the MPP, of course it can track the MPP under real world conditions. A small deviation occurs for both systems after fast increase in insolation level, but both systems succeeded to correct the tracking process. Irradiance level is fixed at 1 sun after increase, but we can see the same oscillation as we saw at constant condition test. Because power oscillation is very small in this scale, it is not visible in the figures.

#### **4.4.3 Testing under changing Temperature condition**

To simulate a changing temperature condition, we applied another signal to the temperature port of solar panel. The temperature is initialized to 25°C and after two seconds it will gradually increase to 50°C within 10 seconds, and simulation will continue for 8 more seconds, so this simulation time is 20 seconds. Again, this change is beyond the real word expectations. Insolation is also fixed at 1 sun during the simulation. Figure 4-14 and Figure 4-15 show the simple Hill climbing and improved Hill climbing MPPT performances under changing temperature condition respectively.

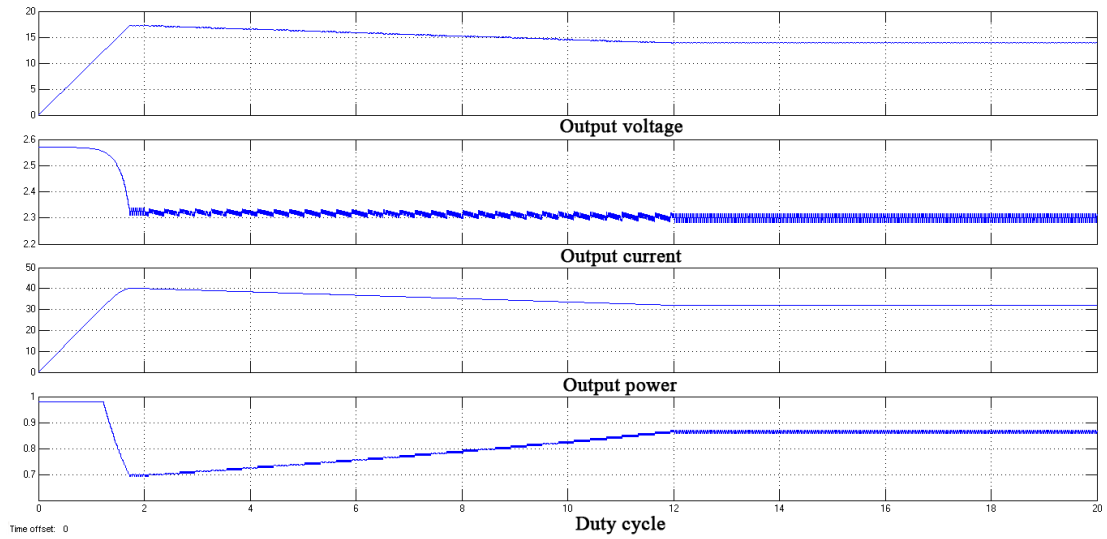


Figure 4-14: Voltage, Current, Power and Duty ratio of Simple system under changing temperature condition

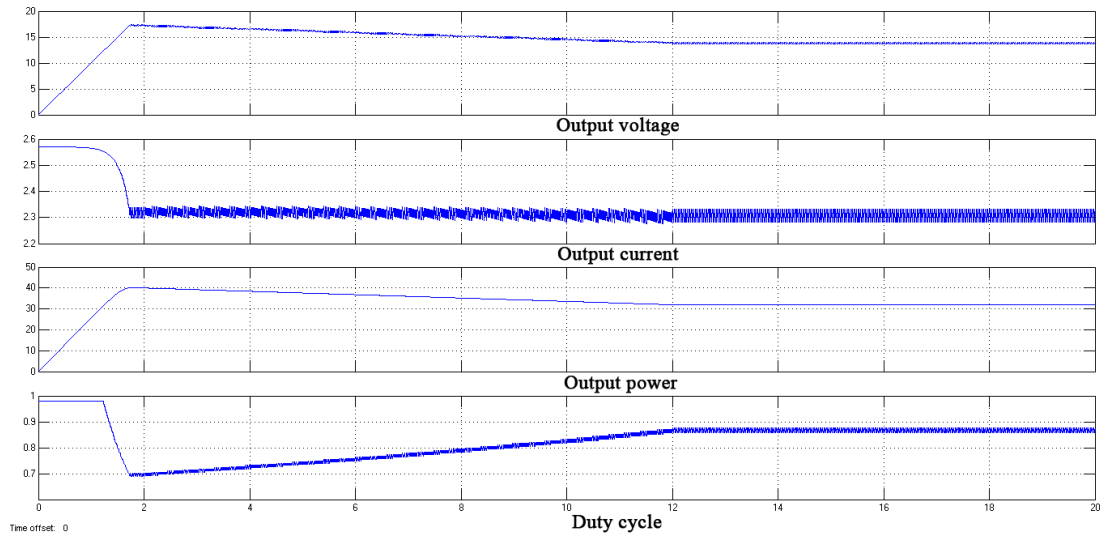


Figure 4-15: Voltage, Current, Power and Duty ratio of improved system under changing temperature condition

Again, there is no big difference in performance of the two systems. Figures show an increase in voltage and power at the beginning of the simulation due to zero initialized  $V_{pv}$ . After 2 second by increasing the temperature, voltage and power drop

slowly. After  $t = 12$  temperature is fixed at  $T = 50^{\circ}\text{C}$  and system follows the steady state performance.

## **Chapter 5**

### **CONCLUSION**

In this thesis a control circuit is used to optimize the power conversion between the solar panel and a proposed load. A 40 watt solar panel (DS-A1-40) is modelled in Matlab and Hill climbing MPPT system is used to connect with a buck converter modelled in Simulink. The whole power system is simulated and tested under varying conditions. The main part of the thesis was to extract the maximum power from a solar panel and deliver it to the load which was 12V battery storage.

The Hill Climbing algorithm is used with maximum power point tracking and a modified algorithm with a different changing rate tested under different conditions. The results show that applying the MPPT method significantly increases the efficiency of a solar power system but there is no remarkable difference in performance of the two algorithms. An incessantly oscillation around the MPP which is observed under steady state operating condition, is due to the nature of Hill Climbing method. This oscillation causes a small power loss which is negligible in IHSSS project application.

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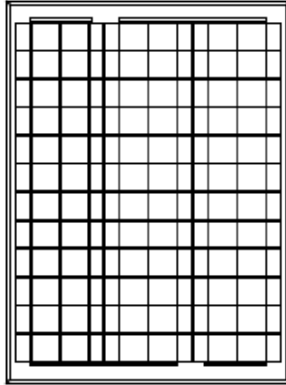
## **APPENDICES**

## Appendix A: Matlab codes for solar cell function

```
function Ipv = DSA140(Vpv,S,T)
% Matlab model for the DS-A1-40 solar panel current for given voltage, insolation and temperature
% Ipv = DSA140(Vpv,S,T) = panel current
% Vpv = panel voltage
% T = Temperature in centigrade degree
% S = Insolation level, each sun is equal to 1000 watts per square meter
n = 1.97;% diode ideality factor
k = 1.38e-23;% Boltzmann constant
q = 1.60e-19;% charge of an electron
Eg = 1.7;% band gap energy in electron volt scale
z = 36;% number of series connected cells
TK = 273 + T; % cell temperature in kelvin
Vt = n * k * TK / q;% thermal voltage
T0 = 273 + 25;% reference temperature in kelvin
Voc_T0 = 21.6 /z;% open circuit voltage for a cell at temperature T0
Isc_T0 = 2.57;% short circuit current at temperature T0
T1 = 273 + 75;% temperature T1 in kelvin
Isc_T1 = 2.7;% short circuit current at temperature T1
Iph_T0 = Isc_T0 * S;% relationship between photo-current and insolation
Xa = (Isc_T1 - Isc_T0)/Isc_T0 * 1/(T1 - T0);% Xa can be obtained from Isc vs T
Iph = Iph_T0 * (1 + Xa*(TK - T0));% relationship between photo-current and temperature
Vt_T0 = k * T0 / q;% thermal voltage at temperature T0
Is_T0 = Isc_T0 / (exp(Voc_T0/(n*Vt_T0))-1);% reverse saturation current at T0
Xb = q * Eg/(n*k);
Is = Is_T0 * (TK/T0).^(3/n) .* exp(-Xb.*(1./TK - 1/T0));% reverse saturation current
Xc = Is_T0/(n*Vt_T0) * exp(Voc_T0/(n*Vt_T0));
dVdI_Voc = - 0.755/z;% extracted from the manufacturer data sheet
Rse = - dVdI_Voc - 1/Xc;% series resistance per cell
Vc = Vpv/z;% cell voltage
Ipv = zeros(size(Vc));%initializing
for j=1:5;%converges to answer using Newton Raphson method
Ipv = Ipv - (Iph - Ipv - Is.*( exp((Vc+Ipv.*Rse)./Vt) - 1))./ (-1 - (Is.*( exp((Vc+Ipv.*Rse)./Vt) - 1)).*Rse./Vt);
end
```

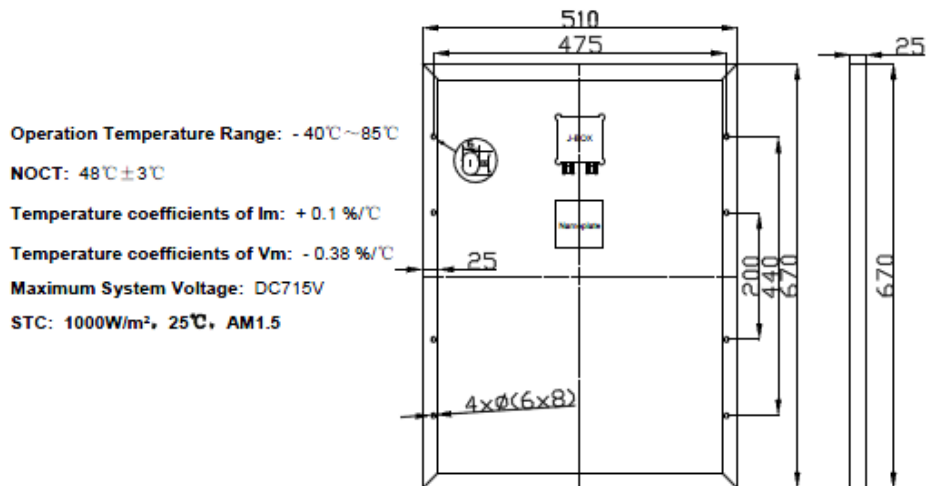
## Appendix B: DS-A1-40 Solar Module Specifications

### DS-A1-40 Panels Specifications



- Solar cells:** 36 pieces crystalline solar cells
- Laminate:** Glass /EVA / TPT (tedlar/pet/tedlar) or TPE
- Front Side:** High-transmission 3.2mm tempered glass
- Back Side:** TPT /TPE
- Frame:** Clear anodized aluminum frame
- Output cable:** Multicontact connectors

Module Type	P <sub>m</sub> (Wp)±5%	V <sub>mpp</sub> (V)	I <sub>mpp</sub> (A)	V <sub>oc</sub> (V)	I <sub>sc</sub> (A)	Module size(mm)	NET(kg)
DS-A1-40	40	17.1	2.34	21.4	2.6	670*510*25mm 26.4"*20.1"*1"	4.1



All the data of this sheet are subjected to change without notice.