# MODELLING AND SIMULATION OF PHOTOVOLTAIC ARRAYS UNDER PARTIAL SHADING CONDITIONS

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# DECLARATION

I confirm that, unless stated otherwise, this work is the result of my own efforts. These efforts include the originality of written material, diagrams or similar pictorial material, electrical or electronic hardware, computer software and experimental results.

Where material is drawn from elsewhere, references to it are included.

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# ABSTRACT

The work presented in this thesis describes the development of a computer-aided design (CAD) package for photovoltaic (PV) arrays. The CAD package, which is based on the MATLAB software, has been specifically developed to investigate the performance of, and obtain the characteristics of a two-dimensional PV array under partial shading conditions. Partial shading is an important phenomenon in PV systems as it can lead to multiplicity of maximum power points (MPP) and complex terminal characteristics, which complicates the requirements placed on the maximum power point tracking (MPPT) algorithm. It is therefore, important that the effects of partial shading, and indeed temperature, on the characteristics of a PV array are studied. The

CAD package developed in this work was tested for characterising a PV panel against the manufacturers' data sheets. The effects of partial shading on the characteristics of PV arrays were investigated for a variety of conditions with particular reference to the complexities partial shading has on the maximum power tracking strategies. The tests concluded that partial shading and varying temperatures resulted in reduced outputs and power losses, thereby affecting the performance of the PV array. The package, which is based on the two-diode model of a PV module, provides a convenient tool for the PV designer and/or a trainee.

## ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and appreciation to my director of studies Mr Nader Anani, who has given me exceptional guidance and motivation throughout this research. I would also like to thank my supervisor Dr Prasad Ponnapalli for his help and advice.

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# TABLE OF CONTENTS

# LIST OF FIGURES

# NOMENCLATURE

| | |
|---|---|
| a | Ideality factor of the diode |
| AM | Air Mass |
| a1 | Ideality factor of D1 |
| a2 | Ideality factor of D2 |
| CAD | Computer Aided Design |
| D | Diode |
| D1 | First diode |
| D2 | Second diode |
| Eg | Band gap energy (1.12 eV for a Poly-crystalline cell) |
| G | Solar insolation (W/m2) |
| GO | Standard solar insolation level of 1000 W/m2 |
| GUIDE | Graphical User Interface Development Environment |
| GUI | Graphical User Interface |
| GW | Giga Watts (109 W) |
| I | Current or output current in Amperes (A) |
| IA | Output current (A) of the array |
| IMP | Current (A) at maximum power |
| IPV | Current (A) generated by incident light |
| IPVSTC | Current (A) generated by incident light at STC |
| IS | Reverse saturation current (A) |
| IS(STC) | Reverse saturation current (A) at STC |
| IS1 | Reverse saturation current (A) for D1 |
| IS2 | Reverse saturation current (A) for D2 |
| IS1(STC) | Reverse saturation current (A) for D1 at STC |
| IS2(STC) | Reverse saturation current (A) for D2 at STC |
| k | Boltzmann's constant (k=1.3806503 ×10-23 J/K ) |
| K I | Thermal co-efficient of short-circuit current (A/°C) |
| KV | Thermal co-efficient of open-circuit voltage (V/°C) |

| | |
|---|---|
| Kx | Series group |
| L y | Parallel group |
| MP | Maximum Power |
| MPP | Maximum Power Point |
| MPPT | Maximum Power Point Tracking |
| MW | Mega Watts (106 W) |
| N | Number of panels |
| NS | Number of cells in series |
| P | Power or output power in Watts (W) |
| PA | Output power (W) of the array |
| PME | Experimentally calculated maximum power (W) |
| PMP | Iteratively calculated maximum power (W) |
| PV | Photovoltaic |
| q | Electronic charge (q=1.6021765 ×10-19 C) |
| RES | Renewable Energy Sources |
| RP | Shunt or parallel resistance (Ω) |
| RPmin | Minimum value of the shunt resistance (Ω) |
| RS | Series resistance (Ω) |
| Si | Silicon |
| SPV | Solar Photovoltaic |
| STC | Standard Testing Conditions |
| T | Temperature (°C) |
| T(STC) | Temperature at STC, 25°C |
| V | Voltage or output voltage in Volts (V) |
| VA | Output voltage (V) of the array |
| VMP | Voltage (V) at maximum power |
| VNP | Voltage (V) across a PV panel |
| VOC | Open-circuit voltage (V) |
| VOC (STC) | Open-circuit voltage (V) at STC |
| VP | Voltage (V) across a parallel path |
| Vt | Thermal voltage co-efficient of the diode, kTq-1 (V) |
| VTC | Terminal voltage (V) |
| Vt1 | Thermal voltage co-efficient of D1, kTq-1 (V) |

| | |
|---|---|
| Vt2 | Thermal voltage co-efficient of D2, kTq-1 (V) |
| Vt1(STC) | Thermal voltage co-efficient of D1, kTq-1 (V) at STC |
| Vt2(STC) | Thermal voltage co-efficient of D2, kTq-1 (V) at STC |

# CHAPTER 1 INTRODUCTION

## 1.1 Introduction

International agreements and commitments to reduce carbon and other emissions harmful to the environment have been the driving force behind the growing interest in renewable energy sources (RES). Solar radiation is a significant source of renewable energy and is expected to become a major source of future energy demands (Maki & Valkealahti, 2012). At present, there is a great global demand for energy resources and this will increase further due to various factors. Rapid population growth, significant use of equipment with a high energy consumption rate and the sudden rise in the usage of all modes of travelling has substantially increased energy demand. Due to many vital energy resources being non-renewable, new forms of resources need to be discovered and utilised. This will ensure that the continued growth and demand of the industrialised nations and the emerging economies can be met.

Solar power is gaining popularity and being debated as a potential candidate to our future energy needs. In order to obtain high output power it is vital to study system performance under certain conditions for further improvements and an in-depth understanding of the solar technology. When considering energy production using solar energy, the resulting output power can be reduced, most commonly because of the varying external conditions. External conditions cause hindrances to the path of direct sunlight thereby producing complex characteristics (Maki & Valkealahti, 2012; Patel & Agarwal, 2008).

In the field of Photovoltaic's (PV) complete or partial PV surface shading, changing temperature and level of radiation from the sun (insolation) are some of the more common external conditions. This project proposes a method to study and validate these effects and to discuss the system performance and the results under these conditions.

## 1.2 Aim

To develop and validate a generalised PV array system model, to investigate the effects of partial shading on its operational characteristics and efficiency.

## 1.3 Objectives

- Conduct an extensive literature search on modelling of PV cells;
- Investigate the suitability of a selected set of models of PV modules using simulation studies (MATLAB);
- Review current techniques for investigating partial shading effects;
- Investigate the inclusion of these techniques into PV array models using simulation studies;
- Develop and validate model(s) for simulating the behaviour of a generic two-dimensional array of individual PV modules, including partial shading effects;
- Recommendations for future work.

## 1.4 Background

The alarming rise in the demand and consumption of energy/power throughout the world has led to a global decline in natural fossil fuel resources. At the same time, there has been a significant increase in global warming. Natural fossil fuels or the non-renewable energy resources such as coal, oil and natural gas have limited reserves which will be depleted. Subsequently, this has led to research and development in order to replace certain non-renewable energy resources with renewable ones.

The use of solar radiation as a source of energy is gaining popularity in the modern world. Partial or complete shading is the most common problem when dealing with solar energy as complete/maximum sunlight is not available. This is usually due to the presence of an object in between the rays of the sun and the surface under consideration. Additional hindrances to optimal performance can also occur due to other external conditions such as insolation, weather and temperature. The insolation is defined as the rate of delivery of the solar radiation per unit of a horizontal surface in Watts per metre square (W/m2). Since the PV technology has been around for a number of years, the effects of partial shading has created serious issues for PV based systems, restricting its optimal performance (Li & Zheng, 2011; Moballegh & Jiang, 2011; Ramaprabha et al., 2010; Thakkar et al., 2010).

The focus of this project is to study the effects of partial shading on Solar PV (SPV) arrays under different levels of insolation while considering varying temperature and climatic conditions. However, the physical testing of a SPV setup is difficult and unreliable due to the high cost of field testing, the process is very time consuming and testing under prevailing weather conditions is very difficult (Ramaprabha et al., 2010). One solution to this problem is by using a CAD package which allows users to perform simulations easily and effectively. As simulations are a way of demonstrating the actual workings and the performance of a system, they can be considered as a suitable replacement for physical field testing but experimental validation is also important.

The most common simulation package that is used for PV modules is MATLAB, which is easily accessible and the software has the capability to produce reliable and valid results. As MATLAB has been utilised to design, model, test and simulate various PV modules, a satisfactory outcome can be expected (Bayindir et al., 2011; Babu & Kumari, 2012; Patel & Agarwal, 2008; Ramaprabha et al., 2010). In addition, another useful feature within MATLAB is known as Graphical User Interface Development Environment (GUIDE) (Hunt et al., 2006; The MathWorks, 2012). This feature allows the designer to develop multipurpose Graphical User Interfaces (GUI) and can be used effectively to model PV panels/arrays and graphically display their characteristics.

The accurate and effective simulation of a PV panel/array requires an efficient PV cell model. Many different types of model have been developed and used, where the simplest of them is the single diode model. The design of this standard PV cell model was modified several times and a variant known as the two diode model was developed. This was designed to account for the effect of the recombination of charge carriers and the finite output resistance of a PV cell (Ishaque, Salam & Taheri, 2011).

Firstly in this study; the model of a PV cell, a panel and an array will be developed using MATLAB. A study will then be carried out on each model based on the effects of partial shading and the external conditions (insolation and temperature). The external conditions can be easily changed in order to evaluate the findings of such change of conditions and the level of insolation. The characteristics that are required to determine and modify the performance of a PV system are voltage (V), current (I) and power (P). Therefore, a display of current-voltage (I-V) and power-voltage (P-V) characteristics of PV cells, panel(s) and an array is a suitable method to analyse their functioning and output performance.

## 1.5 Purpose of Study

The foundation of this study is based on the utilisation of solar radiation as a renewable energy resource which when directed towards a PV array generates optimal power/energy. These PV arrays are commonly installed and used in urban areas due to high energy consumption. For this reason, buildings/towers, trees, clouds, dusty and polluted surroundings cause either partial or complete shading on the PV modules. The result is a display of complex characteristics and a significant overall reduction in output power.

In partial shading conditions; the knowledge, understanding and the prediction of characteristics is critical when effectively operating and performing an analysis on a PV panel/array based power system (Bayindir et al., 2011; Patel & Agarwal, 2008; Ramaprabha et al., 2010; TSai et al., 2008). Hence, it is imperative to study the effects of partial shading on a PV system where components like the PV cell, a panel and an array can be easily used as well as modified. The purpose is to study each component individually and then as a combined setup. This will aid in a better understanding of the characteristics. As the testing is not field based but is done using MATLAB, changes can be easily made with respect to the shading levels, PV cell/panel configuration and the external conditions (temperature and insolation). Partial shading causes instability to output characteristics which is the generation of several local maxima (power points) and makes the tracking of a Maximum Power Point (MPP) fairly complex.

## 1.6 Scope of Study

Firstly, modules using different models of PV cells will be modelled in MATLAB and presented. When developing the final PV panel and an array, only the two diode PV cell model will be implemented. The parameters of a commercially available PV module, the MSX-60 (poly-crystalline PV cell), will be used to model the components of the PV panel and the array (University of Maine (UMAINE), 2011).

A technique will be developed using the GUI in MATLAB to show the effects of partial shading (using different insolation and temperature conditions) on the PV cell(s), on a panel and an array.

## 1.7 Main Diagrams

Figure 1 shows a block diagram where a 3x3 PV array (9 PV panels) is presented. The main features that are responsible for its optimal performance, namely: the insolation and temperature are shown as inputs to the system. Also, the “number of cells” option is available as an input in order to view the performance of a panel or an array by varying the quantity of its cells in series.

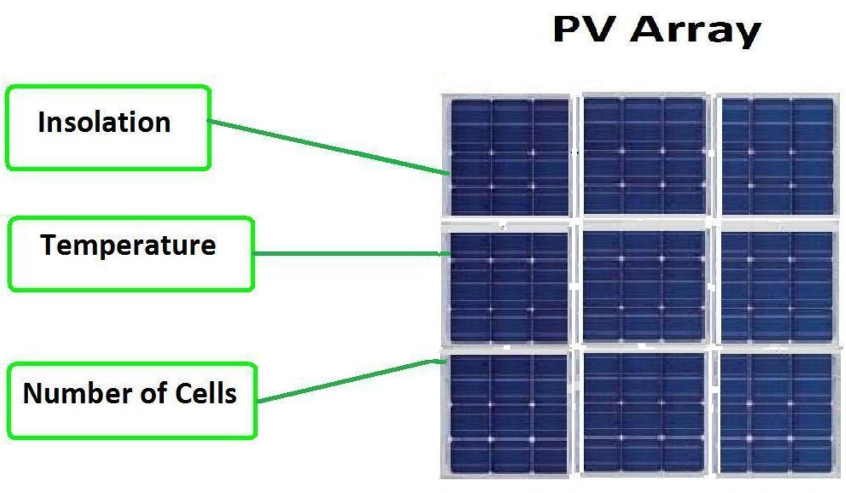



Fig ure **Main Block Diagram**

Figure 2 shows a PV array under normal conditions (no shading, standard temperature and insolation levels). Under these circumstances the PV array should deliver optimal performance and stable characteristics (I-V and P-V).

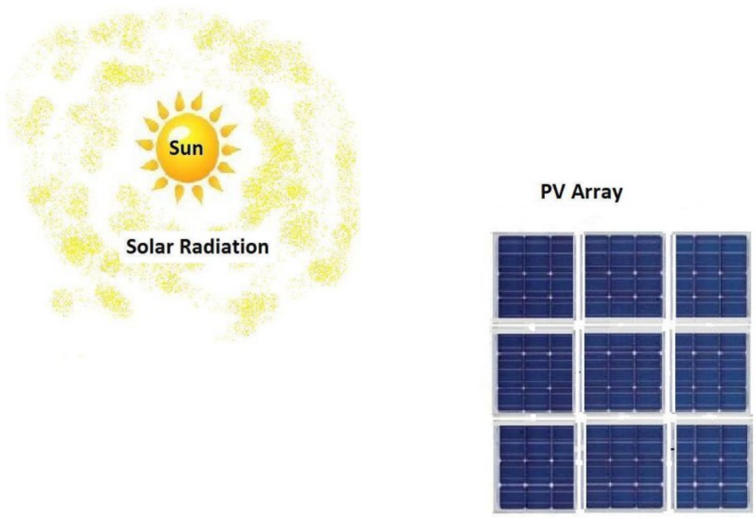
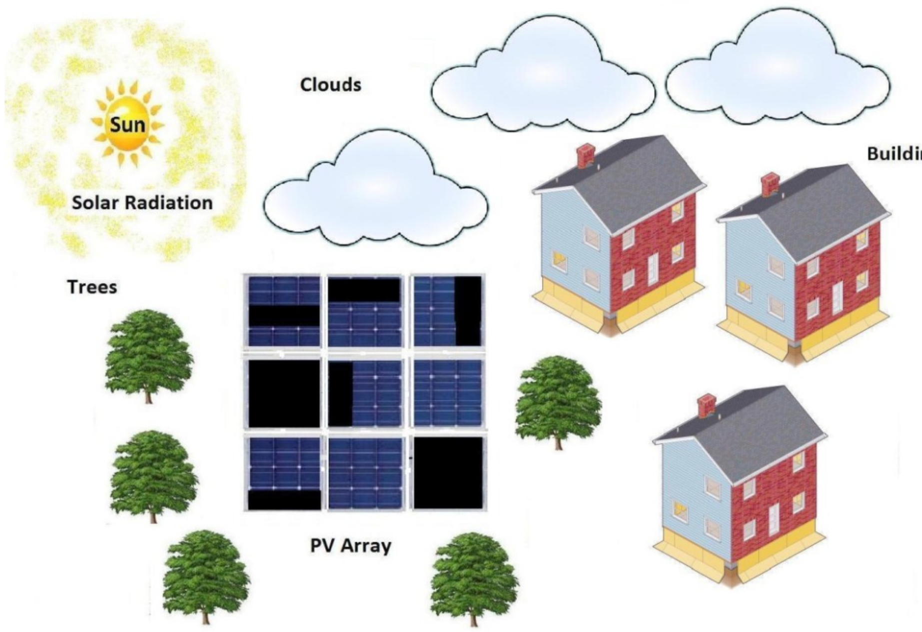


Figure   **PV Array (Normal Conditions)**

Figure 3 shows a PV array under varying/unsuitable conditions (partial shading, varying temperature and insolation levels). The system is surrounded by objects like: trees, buildings, clouds and varying weather conditions. Under these circumstances, the PV array demonstrates poor performance as it delivers low power, instability and complex characteristics (I-V and P-V).

## 1.8 Overview




**Chapter 1 Introduction:** This chapter discusses introduction, aim, objectives, background and the purpose of conducting this study.

**Chapter 2 Literature Review:** This chapter discusses the literature based knowledge on renewable energy and its future, solar radiation, PV cells, panels and arrays, partial shading and the future of PV technology.

**Chapter 3 Modelling of the PV Cells:** This chapter discusses four types of PV cell models along with their characteristics. Their parameters were calculated by using different equations as well as information available in the MSX-60 data sheet.

**Chapter 4 Configuration of a PV Array:** This chapter discusses the built-in protection circuit in the modern PV modules and their PV panel/array configurations.

**Chapter 5 Implementation of the Codes:** This chapter highlights the modelling codes for the MSX-60 PV module (poly-crystalline), panel and an array in the form of a flow chart. The actual codes in the MATLAB script format are shown in the appendices.

**Chapter 6 MATLAB-GUI Model:** This chapter discusses the modelling of a 3x3 PV array as a GUI with adjustable input values of insolation and temperature. This GUI was created in GUIDE and is programmed using the codes in the MATLAB script.

**Chapter 7 Conclusions and Future Work:** This chapter examines the results drawn, while considering the objectives of this study. Also, recommendations for future improvements and enhancements were discussed.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Renewable Energy

The word ‘renewable’ refers to anything that can be restored or regenerated. Renewable energy is a type of energy that is derived from natural resources that are easily accessible and are considered unlimited. This energy is obtained from resources such as: wind (wind power), the sun (solar power), rivers (hydro-electric power), tides (tidal power) and biogas (bio fuels) (Britannica, 2012).

### 2.1.1 Wind Power

Currently, the most common method of generating renewable energy with wind is through the use of wind turbines and is known as wind power. The main components of these wind turbines are: a rotor and its blades, a tower, gear box, shaft and a generator (World Wind Energy Association (WWEA), 2006). A modern wind turbine can be seen in Figure 4 (Net Resources International (NRI), 2012).

Figure **Wind Turbines (On-shore)**

The wind turbines of the modern era are classed in two different categories: the off-shore and the on-shore wind turbines. The on-shore wind turbines (Figure 4) are the most commonly used turbines that have been installed in numerous countries globally. These wind turbines can be used for either grid-based or off-grid systems. In contrast, the off-shore wind turbines (Figure 5 (Avro, 2009)) are found at sea and are only installed by countries like China and certain European countries like the UK, Germany and Denmark. Countries that experience high windy conditions are the most suitable and ideal locations for the installation of wind turbines.

Figure **Wind Turbines (Off-shore)**

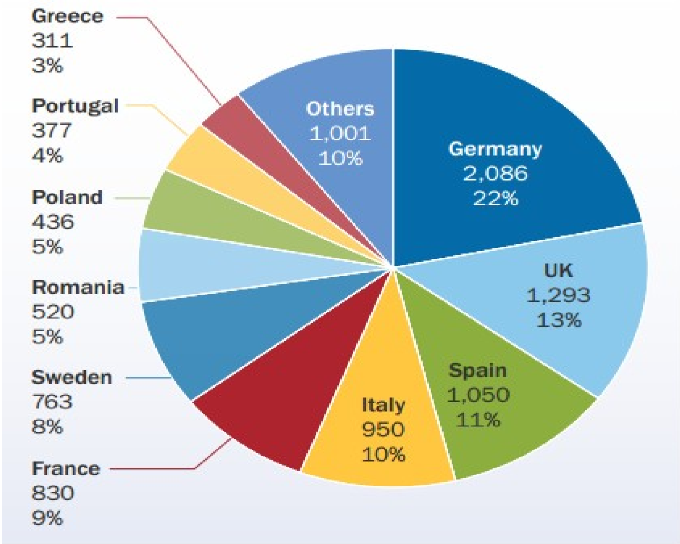
At present, large wind energy farms are operating throughout the world as a source of renewable energy (Electricity) thereby reducing the consumption of non-renewable resources. According to the annual report by WWEA in early 2012, approximately 98 countries are utilising wind power for electricity production with the capacity to produce up to 197 GW at one time (WWEA, 2012).

The largest on-shore wind farm in the world is the Alta Wind Energy Center in the USA, which is operating at an output of 981 MW but has a combined installed capacity of 1,021 MW (American Wind Energy Association (AWEA), 2012). The four largest wind farms are located in the USA followed by China. This demonstrates the dominance of the USA in the production of wind power making them less reliant on non-renewable resources such as coal, oil, gas and nuclear power. It has also be confirmed that currently the total installed wind power capacity by the USA is 50 GW (AWEA, 2012; Murray, 2012).

The largest off-shore wind farm in the world is Walney Wind Farm located in the UK, off the coast of Cumbria, and this has a production capacity of 367 MW (Dong Energy, 2012). Statistics show that the UK is reaching new levels of electricity production from wind as windy conditions overpower the sunny conditions. The British Wind Energy Association (BWEA) confirmed that the total installed capacity of wind power in the UK is approximately 1300 MW (Renewable UK, 2012). As more projects are undertaken and completed globally, the capacity to generate power using wind energy is likely to rise. This will result in a further reduction in the dependency of non-renewable resources. The rising trend of wind power in the European countries has influenced the UK to follow suit.

Figure 6 highlights the European market share (%), as well as the output capacities (MW) for the wind power installations during 2011(European Wind Energy Association (EWEA), 2012). The chart by EWEA shows the dominating EU countries within the field of wind energy. Due to a rise in the installation capacity from previous years, further increase in installation capacity is predicted.

## 2.1.2 Solar Power



The use of solar energy to generate power is a recent phenomenon and is known as solar power. Past civilisations relied on the sun to produce light and heat for daily activities. The most common use of this light is through PV cells, which helps to generate electricity when placed under the sunlight (solar radiation). A PV panel/array is made up of many PV cells which are either installed within an individual system (off-grid) or on a very large scale in the form of a solar farm (on-grid). A PV setup consists of a PV panel/array, a platform and an inverter, and either batteries (off-grid) or a direct connection to the grid via a connection to the consumer unit (off-grid/on-grid) (EvoEnergy, 2012). Figure 7 (Focus Technology, 2012) shows the PV setup (panels/arrays) as an off-grid system that is installed for the purpose of running individual loads and off-grid requirements which are on a small scale. Off-grid systems can include PV roofs for houses and buildings, street/car park lighting and small domestic appliances.

Figure **PV Array (Off-Grid System)**

Figure 8 (RRE Solar, 2010), however illustrates the PV setup (panels/arrays) as an on-grid or grid connected system which is installed in the form of a solar farm. The purpose of solar farms is to fulfil higher loads and grid requirements and to provide electricity on a much larger scale.

Figure **Solar Farm (On-Grid / Grid connected System)**

In another recent development, in the field of solar power, is the installation of a PV setup/farm in water in order to use the space provided by ponds, rivers and water reservoirs. An Italian company has become the first to introduce the floating solar panels in the form of a mini solar farm known as the Floating Tracking Cooling Concentrator (FTCC) system (McCue, 2012). The benefit of this system includes utilising unconventional space, developing more enhanced setups and assisting in cooling the panels when exposed to high temperatures. The concept is similar to the popular and widely used solar discs that light up ponds and swimming pools. The increased use of solar power has reduced the consumption of non-renewable energy resources and therefore an increase in PV system installations (solar farms) can be predicted. By the early 2012, global total installed capacity of solar power generation reached to 64.4 GW (British Petroleum (BP), 2012).

Many countries have built solar farms to generate cheap electricity and to replace non-renewable resources. The largest solar farm in the world at present is the Gujarat Solar Park in India, which has an installed capacity to generate 600 MW of solar power at one time (Mæhlum, 2012; The Guardian, 2012). This clearly shows that developing countries such as India are working towards a future in solar energy electricity production. According to the recent reports by the International Energy Agency (IEA) in 2011 and the European

PV Industry Association (EPIA), there are many countries that have established high levels of solar power generation.

The top ten countries with the highest annual output power capacities till the beginning of 2012 include: Germany 24.7 GW, Italy 12.5 GW, Japan 4.7 GW, USA 4.4 GW, Spain 4.2 GW, China 2.9 GW, France 2.5 GW, Czech Republic 2 GW, Belgium 1.5 GW and Australia 1.2 GW (Nelson, 2012).

Many of these countries including Spain, Italy, Australia and the USA have high potential to generate solar power due high levels of insolation based on their location. Additionally, these countries have planned high capacity projects which are being currently installed. It is anticipated that such projects will significantly increase their capacity and decrease the dependence level of non-renewable energy resources in the coming years. The annual BP statistical review 2011 on World Energy, confirms the solar output generation capacities (GW) shown in Figure 9 (BP, 2012).

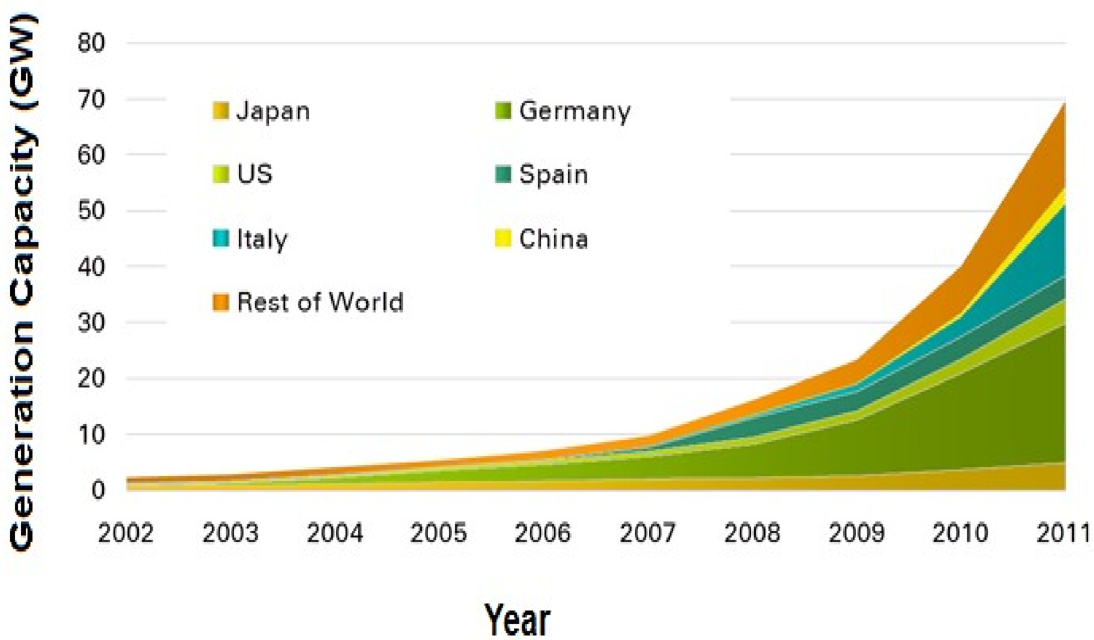



Figure **Solar Power Generation Capacities (GW)**

As sunlight levels play a crucial role in identifying suitable locations for PV system installations, this has not prevented countries like the UK and Canada, even though they are less prone to high annual insolation levels. The UK government has introduced various grants in order to encourage the use of solar power within homes and businesses in an attempt to reduce the CO2 emissions and promote renewable energy. Due to advancements in generating electricity using solar energy, various countries in South Asia, Middle East and Africa have initiated projects to construct solar farms for renewable power generation.

### 2.1.3 Hydro-electric and Tidal Power

Hydro-electric power is generated when the potential and kinetic energy of fast-flowing or falling water is converted into electricity using a water turbine connected to an electricity generator (Britannica, 2012; Renewable Energy Association (REA), 2012). Therefore, a hydro-electric power setup should comprise of: turbines, shaft, rotor and a generator. The hydro-electric power generation can be of two types: small scale and large scale. A small scale setup is a low level electricity production unit that consists of turbines installed in remote areas like villages and farms, as well as near streams. In contrast, a large scale setup is a high level electricity production unit consisting of dams and huge reservoirs.

A hydro-electric screw (small scale setup) can be seen in Figure 10 (HydroScrew, 2011). Other forms of a small scale setup could be a water mill or a set of mini propellers installed in a small stream. Also, a hydro-electric dam (large scale setup) can be seen in Figure 11 (Kompulsa, 2012). Dams are usually used for water storage purposes but more recently they have been utilised in the generation of electricity.

The Three Gorges Dam in China which has an installed capacity of 22.5 GW, is the largest and a well known dam in the world (Clark, 2012; International Rivers, 2012).

Figure **Hydro-Electric Screw**

Figure **Hydro-Electric Dam**

The Asian Development bank (ADB) and the African Development Bank (AFDB) are planning hydro-based projects in South Asia and Africa respectively, due to shortages of water storage and power generation. Hydro-electricity has proven to be an efficient and reliable technology due to modern plants having conversion efficiencies above 90% (REA, 2012). This shows that although the hydro-electric power setup is expensive and its construction is time consuming, it is a great source of economical renewable energy.

Tidal power is another hydro-electric based technology that consists of similar turbine related techniques as a dam, but is dependent on tides and waves in the open seas. Figure 12 (Greenlaunches, 2011), illustrates that a tidal power setup consists of turbine blades, rotor, generator, a tower and a connection to the grid. The waves/tides are a constant source of kinetic energy that causes rotation of the blades within the turbines, thereby generating electricity with the help of an electric generator (Marine Current Turbines, 2012).

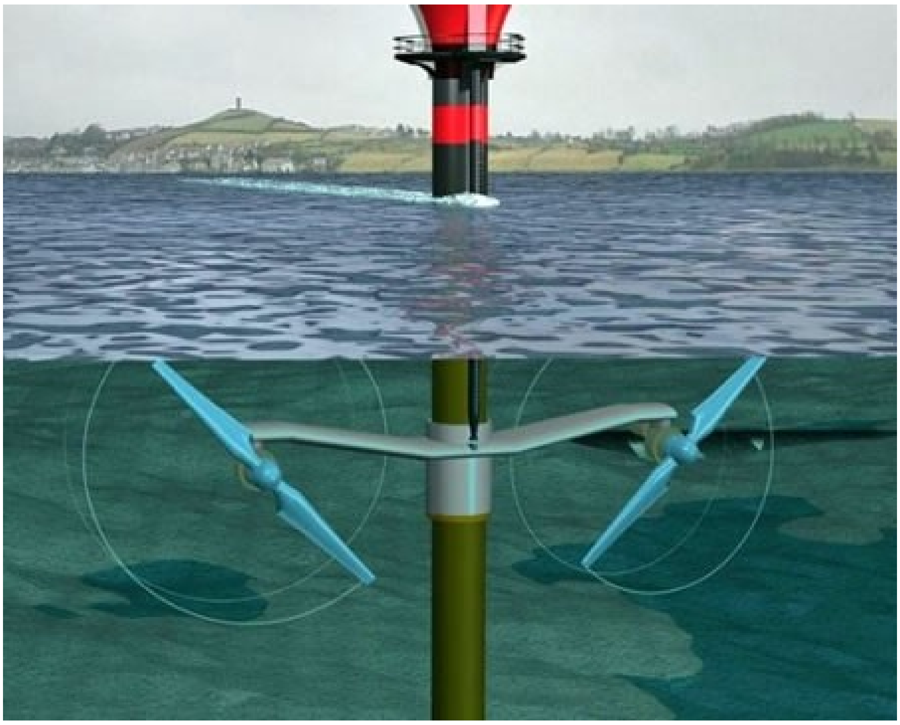


Figure **Marine Turbines**

The structure and function of a Marine turbine is similar to a wind turbine and both are a productive source of renewable energy. As the UK is surrounded by some of the most powerful tides in the world, it is considered to be ideally located for tidal power generation (Shukman, 2012). The UK is home to the world's largest marine energy resource (estimated more than 10 GW) and will play an important part in the UK's development of renewable energy (Marine Current Turbines, 2012).

The UK government plans to increase the capacity/generation level of its renewable and tidal power as this potential energy source is an important asset.

### 2.1.4 Biomass/Fuel Energy

Bio-fuels are derived from biomass and can be used in liquid, solid and gaseous forms. The use of bio mass to generate energy can help in improving waste management and also reduce pollution, greenhouse emissions and the use of fossil fuels (Biofuel, 2010). Figure 13 (Pros and Cons of Biomass Energy, 2012) highlights the variety of materials that can be used to create biomass/fuel thus proving that biomass energy can be produced through the usage of waste material. This also suggests that biomass energy is renewable.

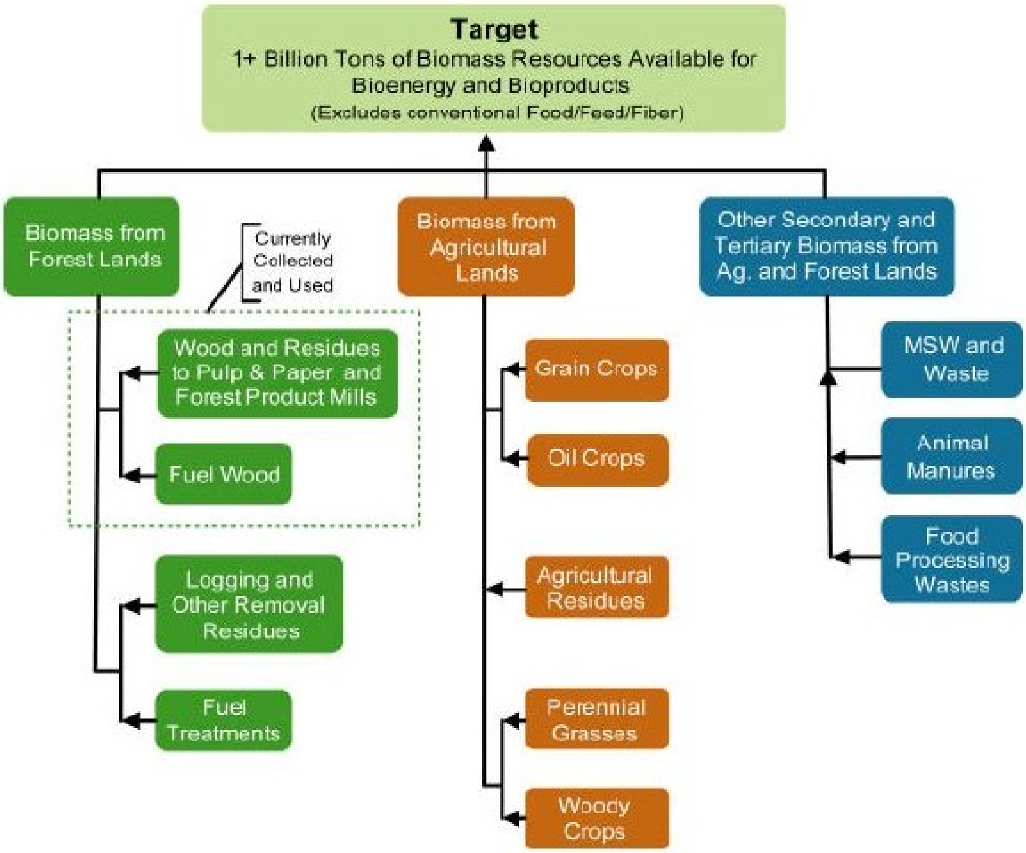



Figure **Biomass/Fuel Resources**

Waste materials can be considered to be valuable as they are a cheap and reliable form of energy production. Further, the usage of waste materials reduces the effect of global warming as it poses a reduced threat to the environment. It is predicted that by the end of year 2020, an equivalent of 19 million tons of oil could be obtained from biomass (Biofuel, 2010). Countries which generate large volumes of waste materials should adopt this method of energy production because bio-fuel is considered to be one of the fuels of the future.

## 2.2 Solar Radiation

Electromagnetic radiation, which includes X-rays, ultraviolet and infrared radiation, radio emissions and visible light emanating from the sun is known as solar radiation (Britannica, 2012). As the sun is a light source, the rate of charge carriers depend on the spectral distribution of solar radiation, where at 6000K its radiation spectrum can be compared to a spectrum of a black body. Figure 14 (Superstrate, 2008) compares the spectral distribution of a black body radiation with extraterrestrial (AM0) and terrestrial (AM1.5) solar radiations.

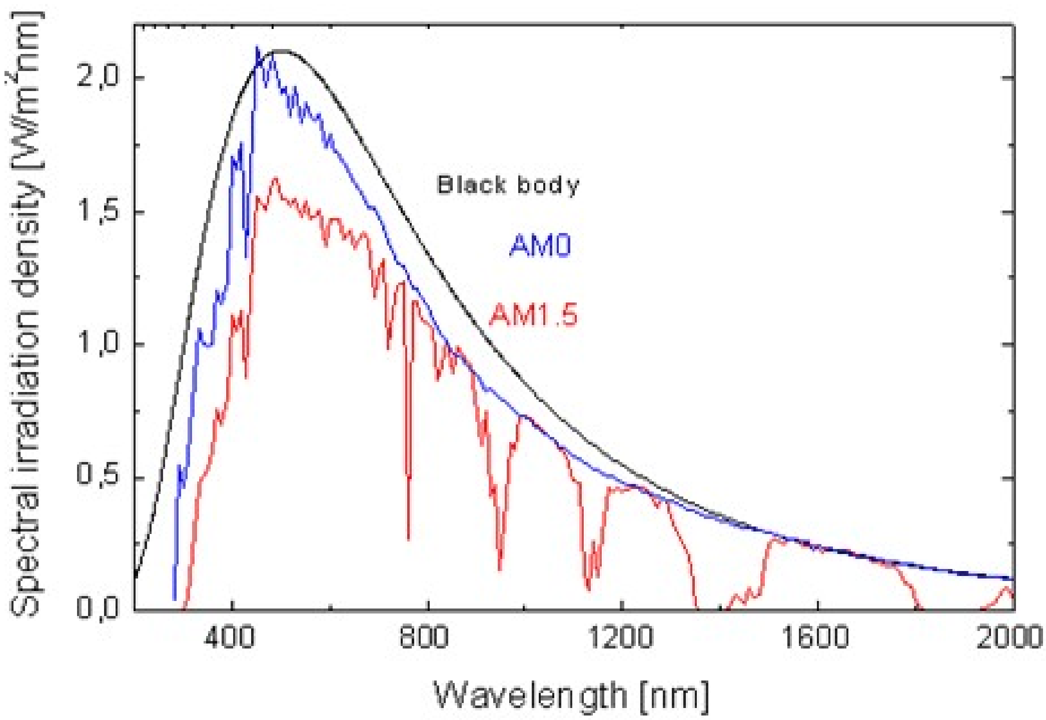



Figure **The Spectral Distribution**

The distance that is travelled through the atmosphere by the sun rays that are incident on the surface of the Earth, is accounted for by a quantity called the air mass (AM). The AM, which lies between the sun and the sun-facing surface and affects the spectral distribution and light intensity, is represented by AM0 for extraterrestrial space radiations and AM1.5 (STC) for terrestrial or Earth's surface.

The standard spectral distribution is important when evaluating a PV cell, therefore the American Society for Testing and Materials (ASTM) defined the two standards for spectral distribution namely: direct-normal and global (National Renewable Energy Laboratory (NREL), 2012).

Figure 15 (Villalva et al., 2009) displays the general idea behind direct-normal and global standard radiations. Here, the direct-normal standard relates to the irradiation when it reaches the sun-facing surface (Earth) without any radiations being diffused. The diffused radiations are solar radiations in a scattered form caused by dust, water molecules and other particles in the atmosphere. The global standard however relates to both the direct as well as the diffused radiations.

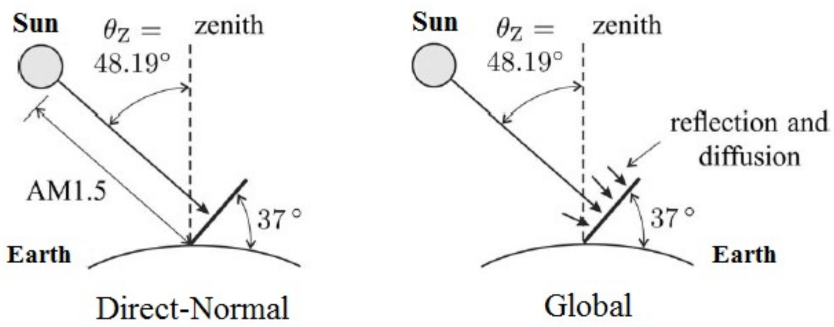



Figure **The Direct-Normal and Global Radiations**

AMx specifies the length for the path of solar radiation through the atmosphere where coefficient “x” is the actual length for the path of the sun rays and θz is the angle between the Sun and zenith (Villalva et al., 2009).

The coefficient “x” can be defined as follows:

$$x = 1\cos\theta z$$

The AM1.5 standard, also shown in Figure 15, corresponds to the sun-facing surface which is tilted at an angle of 37° with the surface of the Earth, at a solar angle of θz = 48.19°. Here, zenith is a point in the sky which is directly above the observer. Large value of “x” results in a longer path between the sun and the sun facing surface as well as a larger air mass. The AM1.5 spectral distributions serve as references for PV cell evaluations and are only estimated values as the intensity and the spectral distribution of solar radiations depend on many factors such as geographic positions and altitude, time of the year, climatic and the atmospheric conditions (Villalva et al., 2009).

## 2.3 The PV Cell

A PV or a solar cell is a semiconductor device that converts the energy from light (sunlight or solar radiation) into electrical energy or electricity through the PV effect (Britannica, 2012; Babu & Kumari, 2012; Villalva et al., 2009). The key component of a PV system is a PV cell, which is made from several types of semiconductors and goes through various manufacturing processes. The most popular semiconductor material is Silicon (Si), so often a single cell consists of a thin film of Si connected to electric terminals, doped to form a P-N junction and covered with a metal grid facing the sunlight.

The physical structure of a PV cell can be seen in Figure 16 (Babu & Kumari, 2012; Villalva et al., 2009), where semiconductor layers and other important aspects are shown.

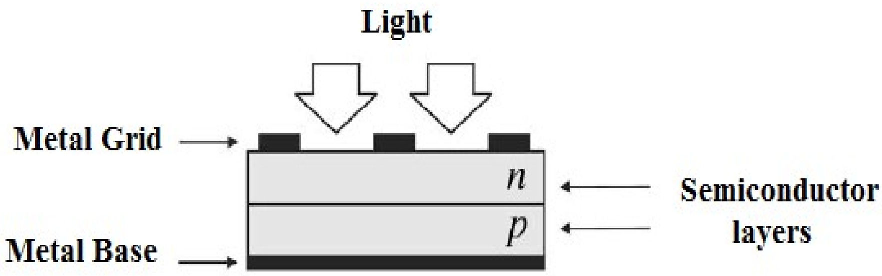
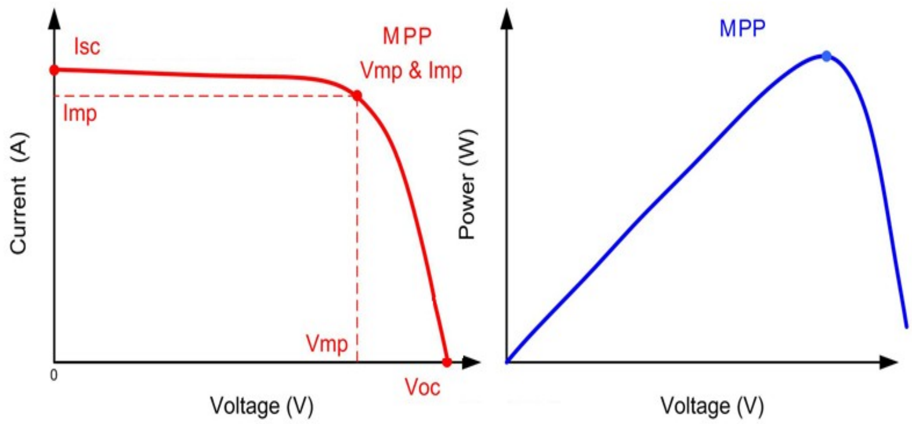



Figure **A PV Cell**

Solar radiation from sunlight consists of photons with different energy levels and the incidence of light that falls on the PV cell generates the charge carriers, which in turn create an electric current (Villalva et al., 2009). If these photons are at a higher energy level, they will generate charge carriers with energy equal to the band gap energy of the semiconductor while the rest of the energy is dissipated as heat. The photons at energy levels lower than the band gap energy are useless and generate no electric current at all. Due to this, the rate of generation of charge carriers is dependent on the incident light frequency and the ability of the semiconductor to absorb this incident light. The ability of the semiconductor relies on factors like the band gap energy, intrinsic concentration of charge carriers and the recombination rate.

### 2.3.1 The Characteristics of a PV Cell

A PV cell, when subjected to certain levels of light intensity, gives an output in the form of voltage V (V), current I (A), and power P (W). The values of V, I and P display the performance and help in determining the characteristics of a PV cell where I-V is current-voltage and P-V is power-voltage. The PV cell gives non-linear characteristics which need to be studied and analysed while keeping in mind the factors that affect them (Maki & Valkealahti, 2012; Patel & Agarwal, 2008; Salam, Ishaque & Taheri, 2010). Figure 17 (Sclocchi & Williams, 2012), shows the characteristics of a standard PV cell. Here **ISC** is the short-circuit current, VOC is the open-circuit voltage, MPP is the maximum power point, IMP and **VMP** are the current and voltage at MPP respectively.




Another important point to consider is that, at VOC the value of ISC is equal to zero and similarly at the point of ISC the value of VOC is equal to zero (Babu & Kumari, 2012; Villalva et al., 2009).

The PV cell performance depends on factors such as the cell material, atmospheric and cell temperature, intensity of the sunlight, inclination angle towards the sun and the irradiation mismatch of the cells. The most important factors that affect the PV cell are: insolation and temperature, where the greater the insolation, the greater will be the output (I & V) but on the other hand, the higher the temperature of the cell, the lower the output voltage (V) will be (Sclocchi & Williams, 2012; Solar4living, 2010). Winter weather and high altitude can also result in low insolation values and as with any other electronic device, the solar cells operate better when kept cool.

### 2.3.2 The PV Panel and an Array

The PV panels are developed from PV cells by connecting them in a series and/or parallel configurations. A simple cell, panel and an array can be seen in Figure 18 (Solar4Living, 2010).

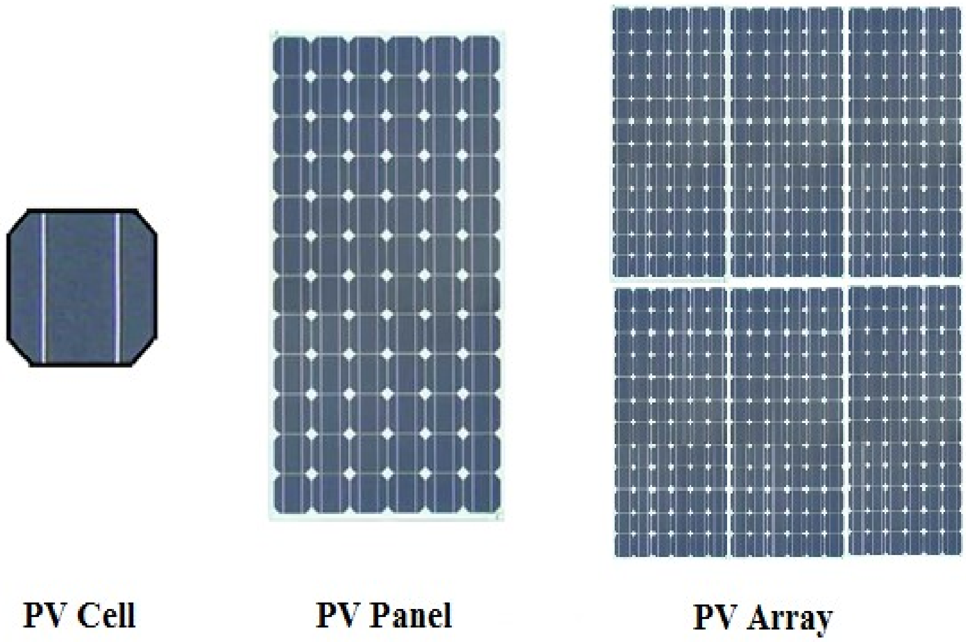



Figure **Cell, Panel and an Array**

The figure clearly shows that the PV panel was assembled using several cells in series and parallel configurations. The PV array in this case was assembled using 6 PV panels, also in series and parallel configurations. In both of these cases, the configurations are undertaken in order to get the required voltage and output power (Solar4Living, 2010).

When the cells are connected in series, the total voltage is the sum of the voltages from each individual cell thereby increasing the output voltage. The output current remains constant and equal to the current of a single cell. On the contrary, when the cells are connected in parallel, the total current is the sum of the currents from individual cells thereby increasing the output current and the output voltage remains constant and equal to the voltage of a single cell.

### 2.3.3 Types of PV Cells

There are many types of PV cell that are readily available and the most common difference between them is their material. The efficiency of a solar cell is usually based on the material used to manufacture the cell. As previously mentioned, the most common material used is Si and 90% of PV system's sales in 2011 were all of Si based cells (NREL, 2012).

At present there are four types of Si based PV cells that are commercially available and can be used for many applications (EvoEnergy 2012; NREL, 2012).

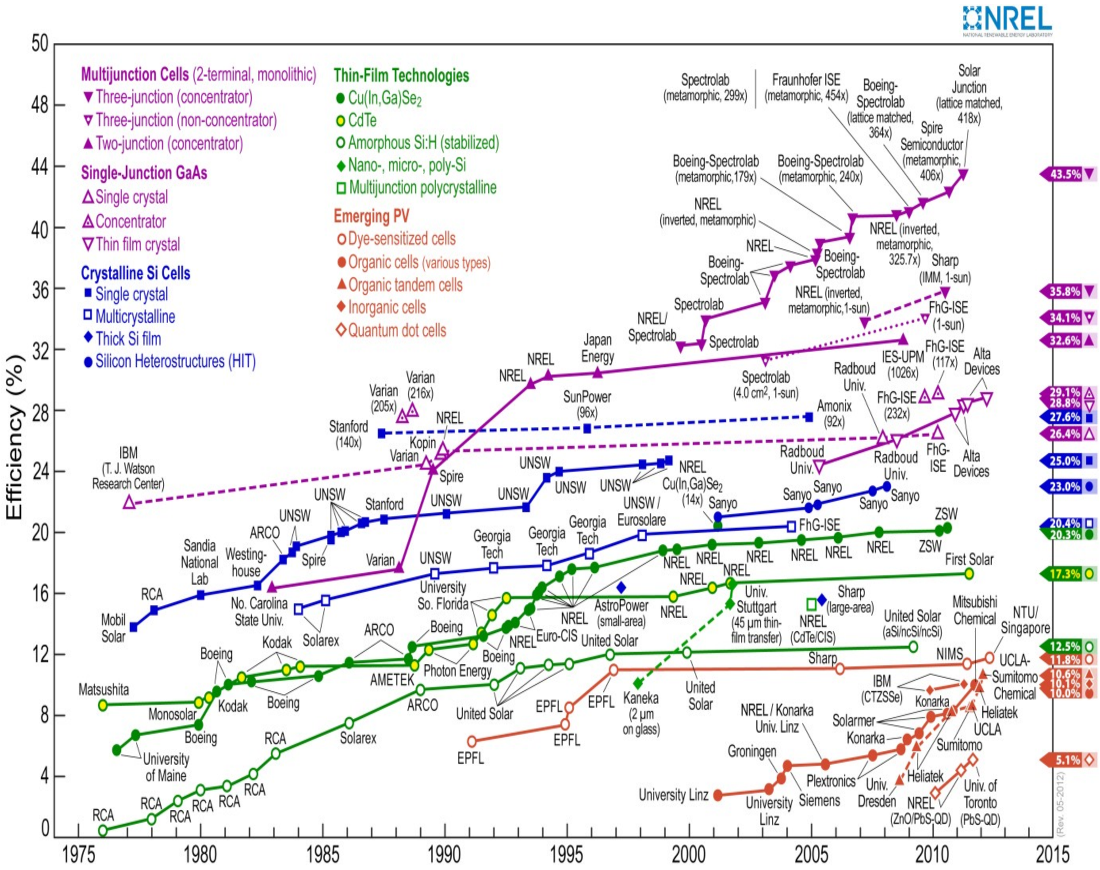
1) **Mono-crystalline Silicon PV:** To produce mono-crystalline Si, the crystal of Si is grown from pure molten crystal. These cells have an efficiency of 13-17% and are classed as the most efficient among the three main types of crystalline cells. They are also one of the most expensive cells available today.

2) **Poly-crystalline Silicon PV:** They are also produced in a similar way to mono-crystalline cells but a casting process is used. When cooled down, these cells set in a poly-crystal form. The cells have an efficiency of 11-15% and the blue colour appearance is due to the application of an anti-reflective layer.

3) **Amorphous Silicon PV:** This type of cell is a non-crystalline Si based cell and fewer raw materials are required in their production. The cells are used for small purposes and have very low efficiencies ranging between 6-8%.

4) **Hybrid PV:** This type of the PV cell uses two different techniques and is made up of mono-crystalline cells covered with an ultra-thin amorphous Si PV layer thereby making them very expensive. This helps the cell to perform at high temperatures and provides an efficiency of 18+ %.

Figure 19 (NREL, 2012), shows several materials and the different types of cells used in the modern PV industry along with their output efficiencies. This diagram also shows the expected increase in efficiency levels up to 2015.




## 2.4 PV Technology and its Uses

As the concept of PV's has been around for some time, new advancements have been made and the technology is now compatible with various types of equipment and systems that are installed at a number of locations.

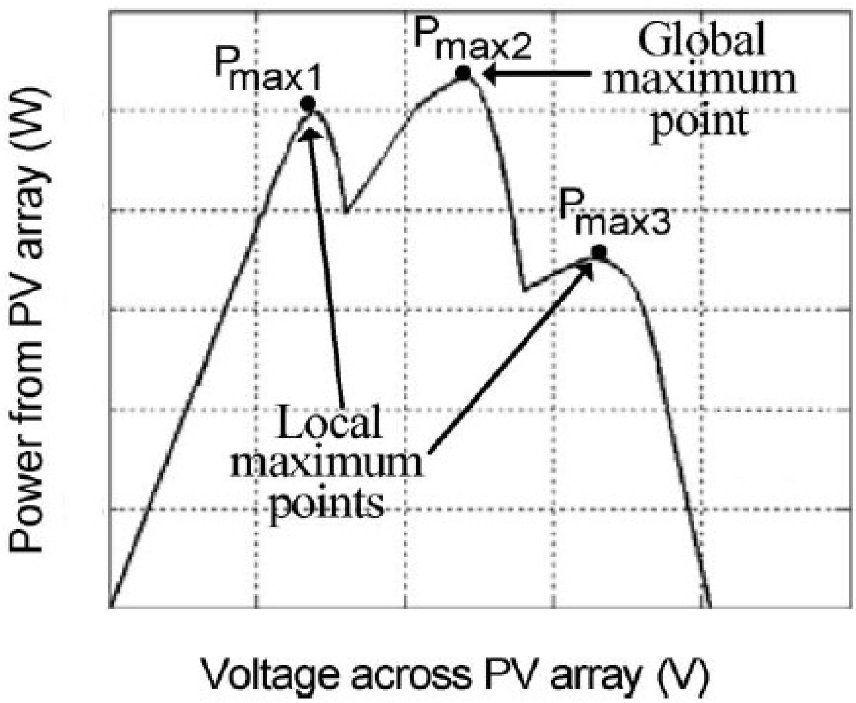
New materials of PV cells have recently been introduced and new techniques have been developed to increase the efficiency of a PV based system (NREL, 2012). Current PV systems are used on roof tops of homes, small or large buildings, as solar farms (on-grid), as off-grid systems like street lights, farm houses/light houses, telephone booths, mobile phone charging stations, power supply for caravans, satellites in space, water pumps/boilers and small appliances such as mini solar fans, solar lamps, battery chargers and calculators (EvoEnergy 2012; Solarbuzz, 2012). With expected improvements in PV technology, such future uses of PV systems may include improved solar-water farms, space vehicles, cars, un-manned drones etc.

## 2.5 Partial Shading and its Effects

Partial shading is a condition or those circumstances under which a PV cell, panel or an array under-performs and delivers low power, instability and complex I-V and P-V characteristics (Li & Zheng, 2011; Maki & Valkealahti, 2012; Moballegh & Jiang, 2011; Patel & Agarwal, 2008; Ramaprabha et al., 2010; Thakkar et al., 2010). Mostly, partial shading occurs when certain PV cells on a panel or an array are shaded from direct sunlight. Research shows that most shading occurs due to surrounding trees, cloud cover, buildings/houses, bird droppings, dust/leaves, water and the tilt angle of the solar panel/array. Complete shading also creates similar problems for PV systems but is not discussed as much as partial shading

Figure 3 (Page 15) identifies partial shading and the many causes behind it. Here, the trees, nearby buildings and clouds are the main reasons for partial shading. Other reasons, not shown in the diagram, also affect the performance of a PV system and include varying temperatures, weather conditions and insolation levels.

The P-V characteristics shown in Figure 17 (Page 30) can represent an array under normal conditions. However, the example seen in Figure 20 (Patel & Agarwal, 2008), demonstrates how the P-V characteristics of a PV array can be affected by partial shading and varying conditions. The P-V curve has multiple peaks therefore it has multiple Maximum Power Points (MPP) and in this case there are three. There is only one global MPP and two local MPP’s, where the global MPP has the highest value of MPP within the P-V curve.



The MPP’s need to be studied and analysed in order to verify the possible output as well as locate MPP’s available throughout the system at certain conditions. Due to this reason, an MPPT algorithm must be applied to a system to help in tracking the MPP in all conditions which should result in an increased output and an improved efficiency.

# CHAPTER 3 MODELLING OF THE PV CELLS

## 3.1 The Ideal PV Cell Model

An Ideal PV cell model consists of a photocurrent generator $I_{PV}$ and a diode parallel to it as seen in Figure 21 (Villalva et al., 2009). This PV cell is also known as a single diode PV cell and its characteristics can be mathematically defined by equation (3.1.1).

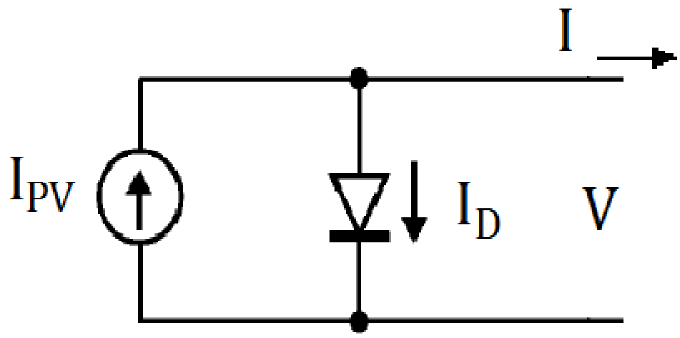



Figure **The Ideal PV Cell**

$$I = I_{PV} - I_S\left(\exp\frac{V}{aV_t} - 1\right) \quad \text{------------------- } (\mathbf{3.1.1})$$

Here I is the output current, $I_{PV}$ is the current generated by the incident light from the sun, $I_S$ is the reverse saturation current, V is the output voltage, $V_t$ is the thermal voltage co-efficient of the diode and a is the ideality factor and is the measure of how closely the diode follows the ideal equation. Also, $I_{PV}$ is represented by equation (3.1.2) and $I_S$ is represented by equation (3.1.3) (Villalva et al., 2009).

$$I_{PV} = [I_{PV_{STC}} + K_I (T - T_{STC})]\frac{G}{G_0} \quad \text{--------------- } (\mathbf{3.1.2})$$

$$I_S = I_{S_{STC}}\left(\frac{T_{STC}}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right] \quad \text{----------------- } (\mathbf{3.1.3})$$

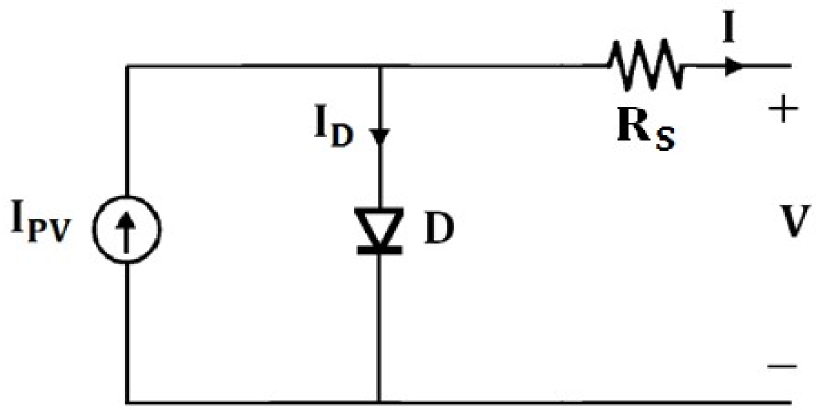
Here T is the temperature, T (STC) is the temperature at standard testing conditions (STC) (insolation is 1000 $W/m^2$, AM is 1.5 and temperature is 25 °C), $I_{PV(STC)}$ is the current generated by the incident light at STC, G is the solar insolation, $G_0$ is the standard solar insolation level (1000 $W/m^2$), $K_I$ is the short-circuit current co-efficient in A/°C , $I_{S(STC)}$ is the reverse saturation current at STC, $E_g$ is the band gap energy (energy required to free an electron from its combined state) of the semiconductor, q is the electronic charge ($q = 1.6021765 \times 10^{-19}$ C) and k the Boltzmann's constant ($k = 1.3806503 \times 10^{-23}$ J/K ). For a poly-crystalline PV cell, $E_g$ is equal to 1.12 eV. The terminal voltage $V_{TC}$ is defined as follows:

$$V_{TC} = V_{ocSTC} - K_V \left(T - T_{STC}\right) \qquad \text{-----------------} \ (\mathbf{3.1.4})$$

Here $V_{ocSTC}$ is the open circuit voltage at STC and $K_V$ is the open-circuit voltage co-efficient in V/°C . For an ideal diode, $I_{PVSTC} = I_{SSTC}$.

## 3.2 Single Diode PV Cell Model with Series Resistance

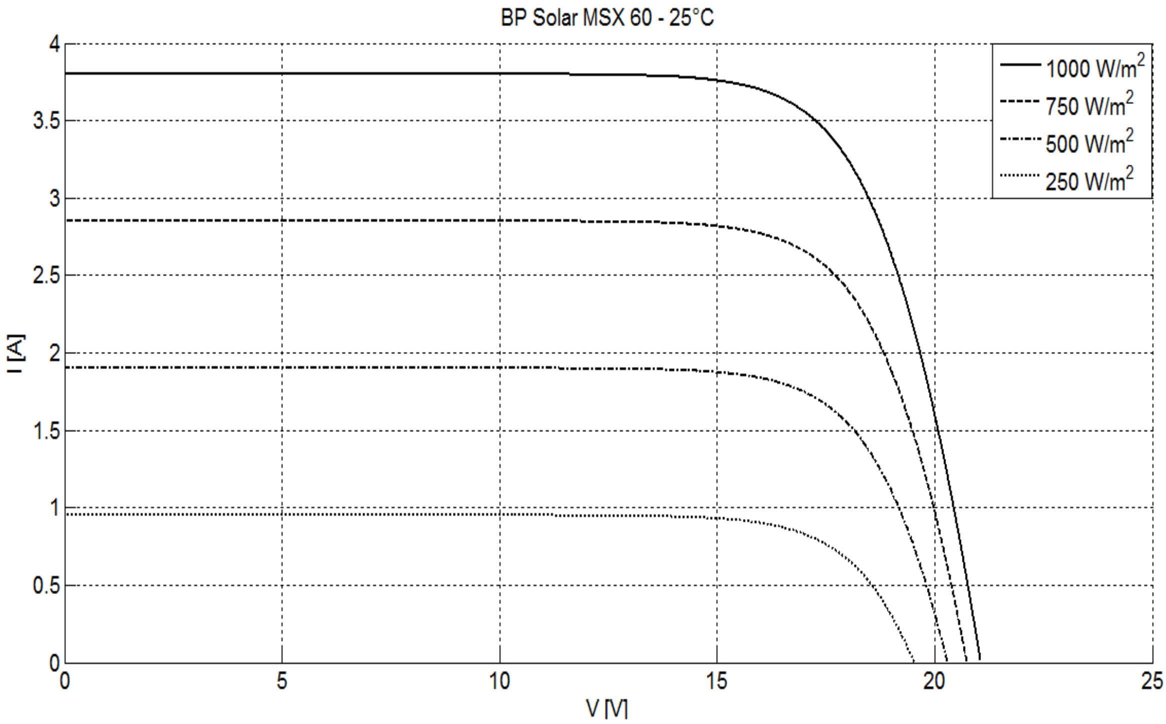
The single diode PV cell model or the standard PV cell model consists of a series resistor $R_S$ as an additional component when compared with an ideal PV cell and can be seen in Figure 22 (Villalva et al., 2009; Walker, 2005).

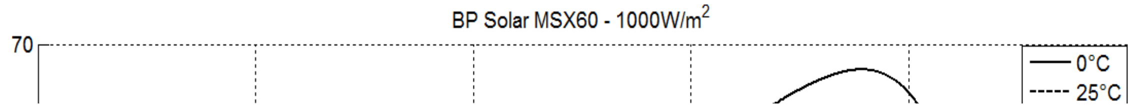


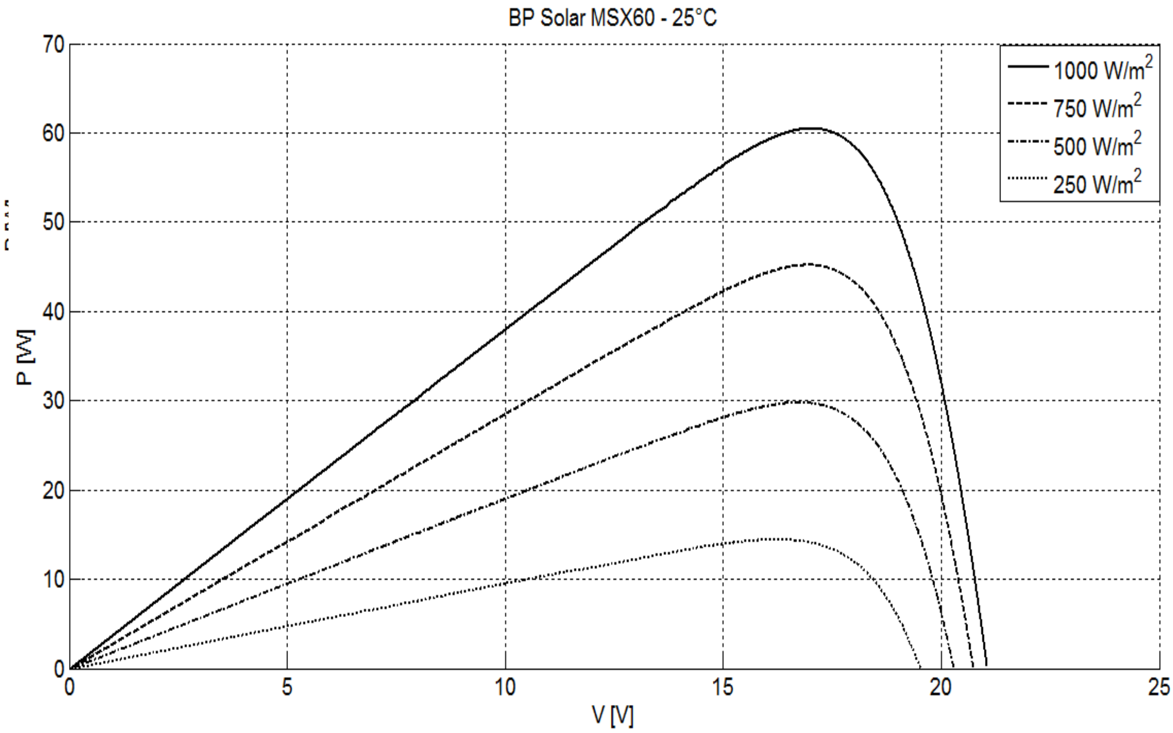

The I-V characteristics are presented in equation (3.2.1) (Villalva et al., 2009; Walker, 2005), where, I is the output current and $R_S$ is the series resistance. Refer to Table 1 (Page 49) for normal parameters but the value of $R_S$ is 0.357Ω and a is equal to 1.

$$I = I_{PV} - I_S \left[\exp\left(\frac{V + IR_S}{aV_t}\right) - 1\right] \qquad \text{---------------} \ (\mathbf{3.2.1})$$

The I-V (Figure 23) and P-V (Figure 24) characteristics for the MSX-60 (UMAINE, 2011) are shown, where the value of temperature is varying and the insolation is set at 1000 W/m2. Also, while using the same model, the I-V (Figure 25) and P-V (Figure 26) characteristics for MSX-60 show a varying insolation when the temperature is set at 25°C.

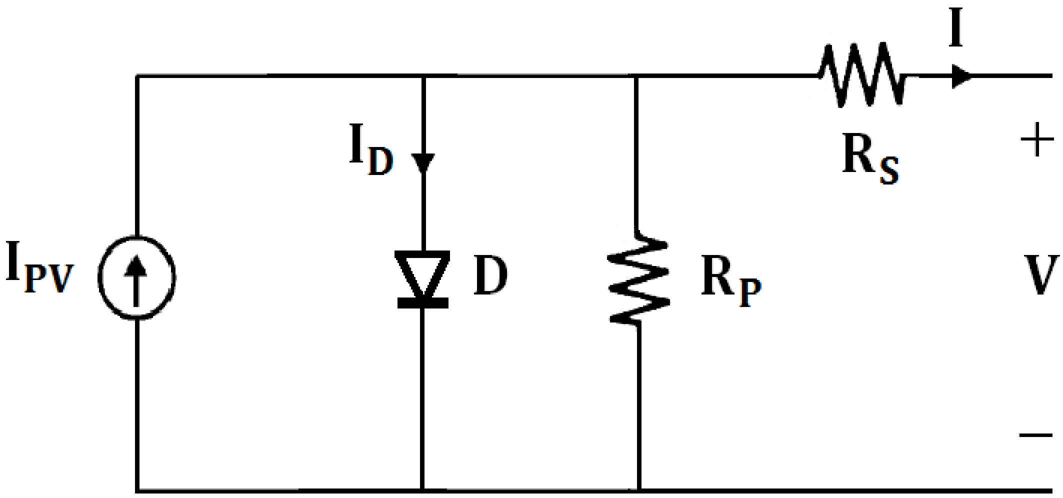


## 3.3 Single Diode PV Cell Model with Series and Shunt Resistances

This PV cell model consists of RS  as well as a shunt resistor RP connected in parallel. The PV cell can be seen in Figure 27 (Azab, 2009; Villalva et al., 2009; Ramaprabha & Mathur, 2009).




The shunt resistance was previously assumed to be infinite, but as there is a small amount of leakage current flowing to ground, a shunt resistance is added to account for this leakage current. The I-V characteristics equation for this PV cell is shown in equation (3.3.1) (Azab, 2009; Villalva et al., 2009; Ramaprabha & Mathur, 2009). Refer to Table 1 (Page 49) for normal parameters but the values for RS is 0.357 Ω, RP is 176.4 Ω and a is equal to 1.

I= IPV – IS expV+IRSaVt- 1- V+IRSRP ------------------ (**3.3.1**)

Equations (3.3.2) and (3.3.3) represent certain improved equations for IPVSTC and  IPVSTC (Villalva et al., 2009).

IPV(STC)=RP+ RSRP ISCSTC ------------------------ (**3.3.2**)

ISSTC=IPVSTC- VocSTCRP[expVocSTCaVt(STC)- 1] ------------------------ (**3.3.3**)

At certain given values of temperature and insolation, equation (3.3.3) becomes equation (3.3.4).

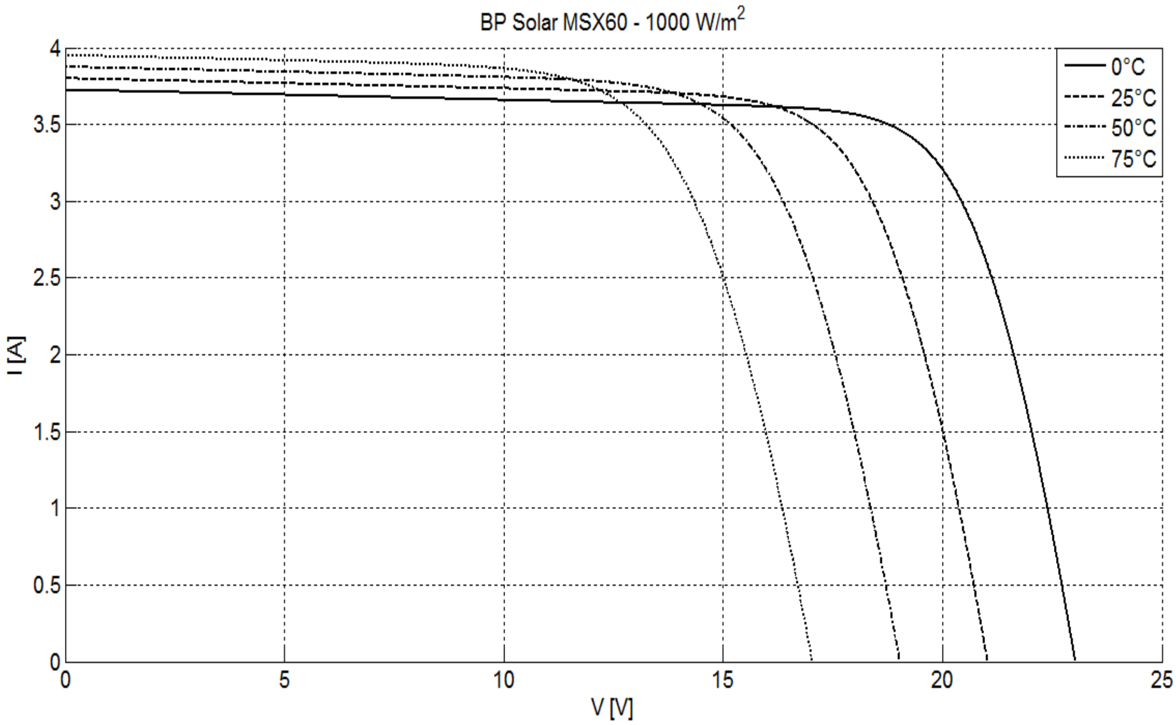
IS=IPV- VTCRP[expVTCaVt - 1] ------------------------ (**3.3.4**)

The ISC is the short-circuit current and ISC(STC) is the short-circuit current at STC. IPV and VTC can be calculated using equations (3.1.2) (Page 36) and (3.1.4) (Page 37) respectively.

Now, this model is used to show the I-V (Figure 28) and P-V (Figure 29) characteristics for the MSX-60, where the value of temperature is varying and the insolation is set at 1000 W/m2.

Also, using the same model, the I-V (Figure 30) and P-V (Figure 31) characteristics for the MSX-60 can be seen, when the insolation is varying while the temperature is set at 25°C.

Figure **I-V Characteristics at an Insolation of 1000 W/m2**



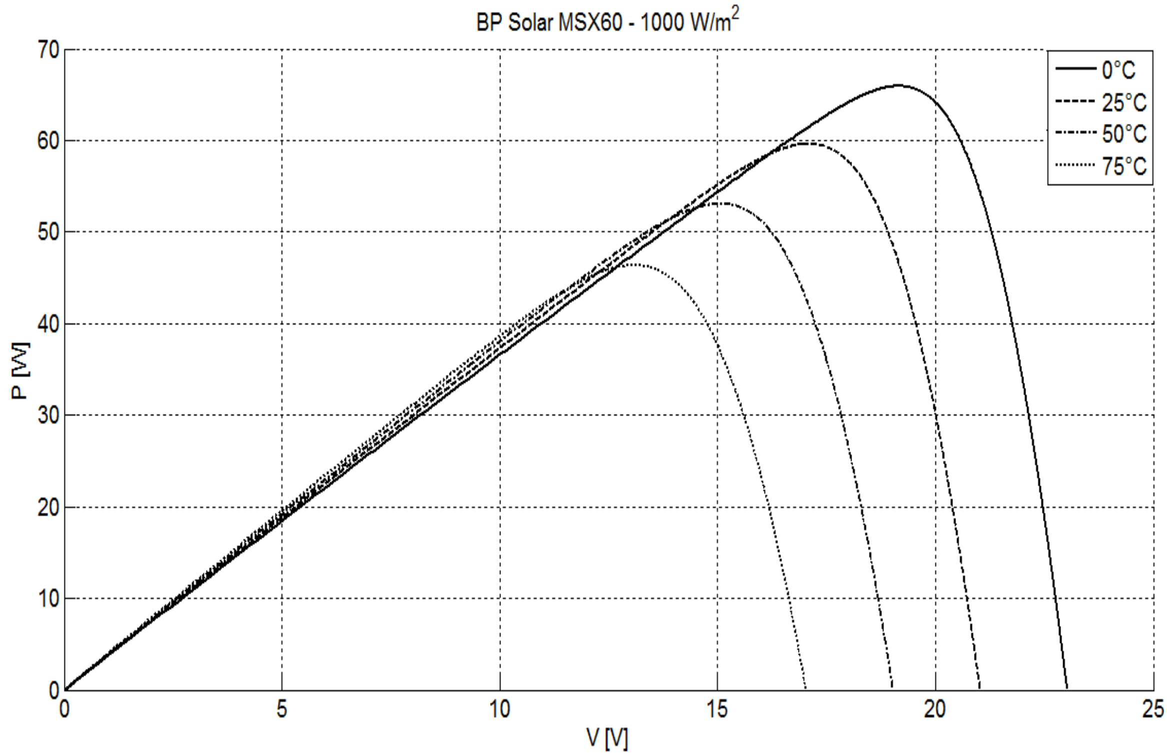
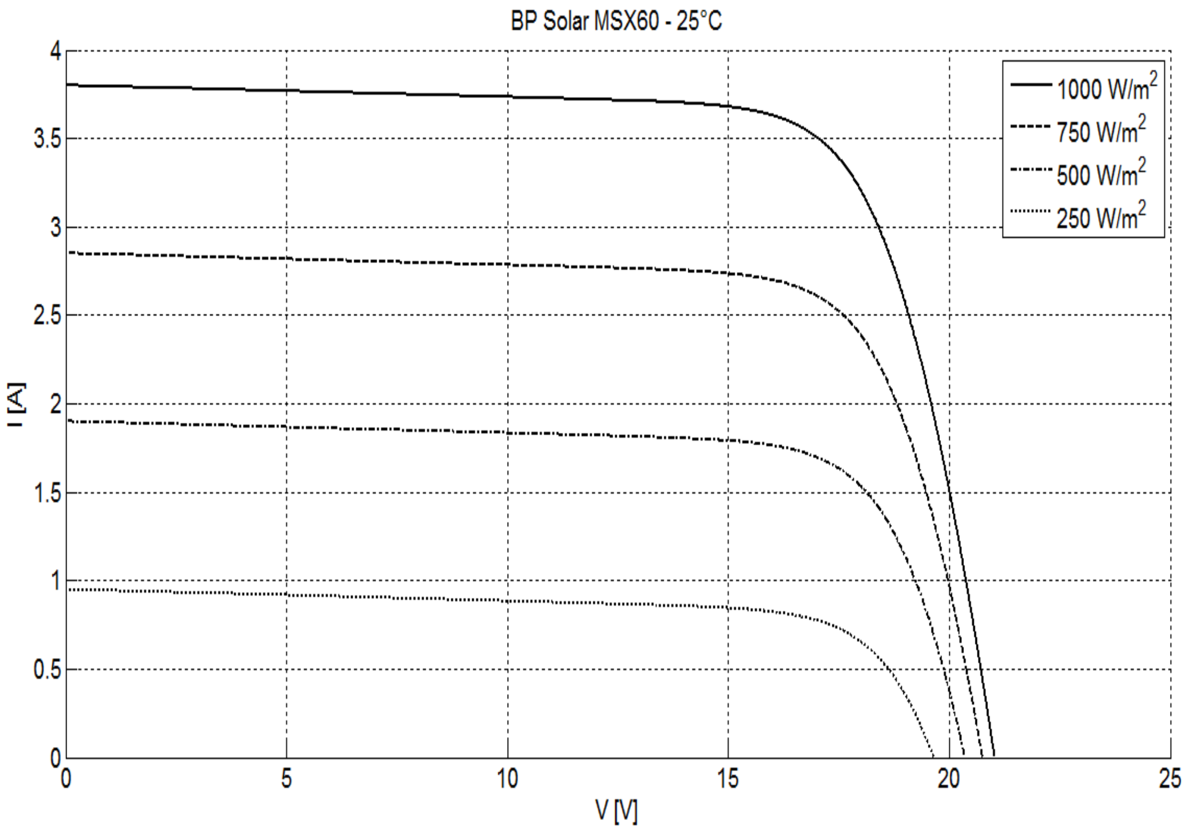



Figure **P-V Characteristics at an Insolation of 1000 W/m2**

Figure **I-V Characteristics at a Temperature of 25°C**



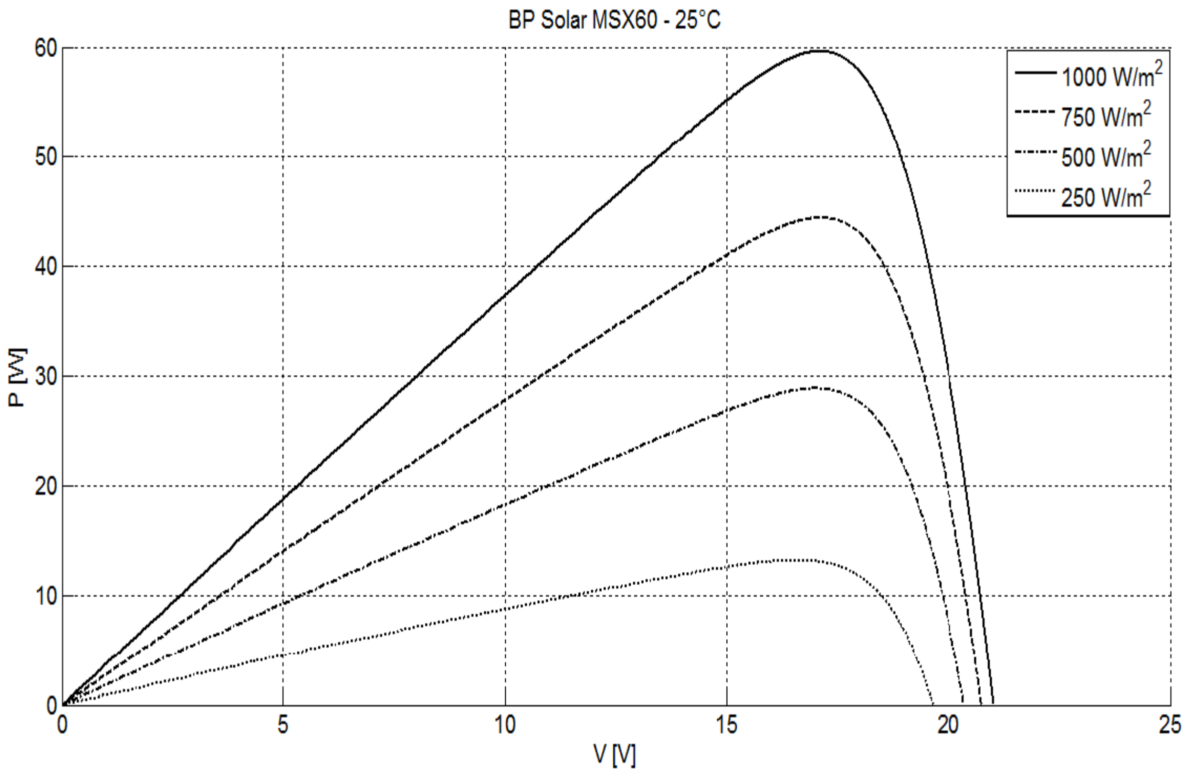
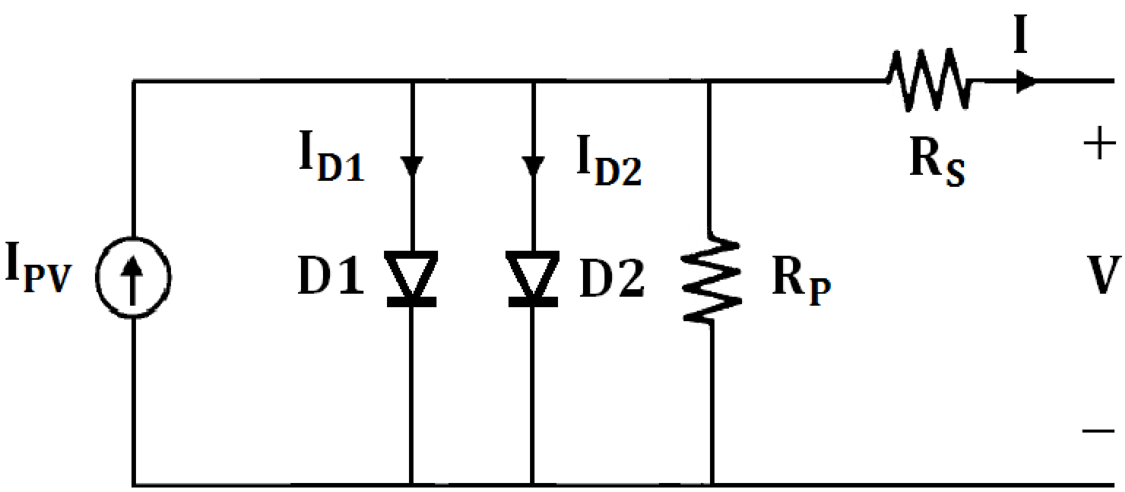



Figure **P-V Characteristics at a Temperature of 25°C**

## 3.4 Two Diode PV Cell Model with Series and Shunt Resistances

This type of a PV cell consists of two diodes (D1 , D2) as well as the series and shunt resistors. Figure 32 (Ishaque, Salam & Taheri, 2011; Salam, Ishaque & Taheri, 2010), shows the two diode PV cell with series and shunt resistances, commonly known as the two diode PV cell model.




As seen in Figure 32, the second diode is connected in parallel with the first diode and the shunt resistance. The second diode is added to cater for the recombination loss. The I-V characteristics equation for this PV cell can be seen in equation (3.4.1) (Azab, 2009; Salam, Ishaque & Taheri, 2010). Refer to Table 1 (Page 49) for normal parameters but the values for RS is 0.357 Ω, RP is 176.4 Ω, a1 is 1.2 and a2 is equal to 2.

I= IPV – IS1 expV+IRSa1Vt1– 1– IS2 expV+IRSa2Vt2– 1–V+IRSRP ------------ (**3.4.1**)

Here IS1 is the reverse saturation current for D1, IS2 is the reverse saturation current for D2, a1 is the ideality factor for D1, a2 is the ideality factor for D2 , Vt1 is the thermal voltage co-efficient of D1 and Vt2 is the thermal voltage co-efficient of D2. It is stated that IS2 is 2-10 times of IS1 and as a result, both are kept equal in order to simplify the equation and reduce the computation, as shown in equation (3.4.2) (Salam, Ishaque & Taheri, 2010).

IS1(STC)=IS2(STC)= [IPV(STC) –(VOCSTCRP)]expVOCSTCa1Vt1(STC) + expVOCSTCa2Vt2(STC)– 2 ------------------ (**3.4.2**)

IS1(STC) is the reverse saturation current for D1 at STC, IS2(STC) is the reverse saturation current for D2 at STC, Vt1(STC) is the thermal voltage co-efficient of D1 at STC and Vt2 (STC) is the thermal voltage co-efficient of D2 at STC. At a given temperature and insolation, equation (3.4.2) becomes equation (3.4.3).

IS1=IS2= [IPV –(VTCRP)]expVTCa1Vt1+ expVTCa2Vt2– 2 ------------------- (**3.4.3**)

Here, IPV and VTC can be calculated using equations (3.1.2) (Page 36) and (3.1.4) (Page 37) respectively.

I-V and P-V characteristics for equation (3.4.1) can be obtained by calculating relevant parameters and deriving a numerical solution in the form of equation (3.4.3.1) (Villalva et al., 2009).

g V,I=I-f V,I=0 ---------------------- (**3.4.3.1**)

A numerical technique known as the Newton-Raphson Method is applied to equation (3.4.1) in an iterative way in order to find a solution. Equation (3.4.4) represents the Newton-Raphson Method (Mathews, 2003; Walker, 2005).

V'=V-gdg/dV ---------------------- (**3.4.4**)

By using equations (3.4.1), (3.4.3), (3.4.3.1) and (3.4.4), the equation comes out to be (3.4.5) while its differential is presented in equation (3.4.6).

g= IPV – IS expV+IRSa1Vt1+ expV+IRSa2Vt2– 2 –V+IRSRP–I ----------- (**3.4.5**)

dgdV= - IS  1a1Vt1expV+IRSa1Vt1+ 1a2Vt2expV+IRSa2Vt2 –1RP ------------- (**3.4.6**)

Now, using this model the I-V (Figure 33) and P-V (Figure 34) characteristics for the MSX-60 are shown, where the temperature is varying but the insolation is set at 1000 W/m2. Similarly by using the same model, the I-V (Figure 35) and P-V (Figure 36) characteristics for the MSX-60 are displayed by varying the insolation when the temperature is set at 25°C.

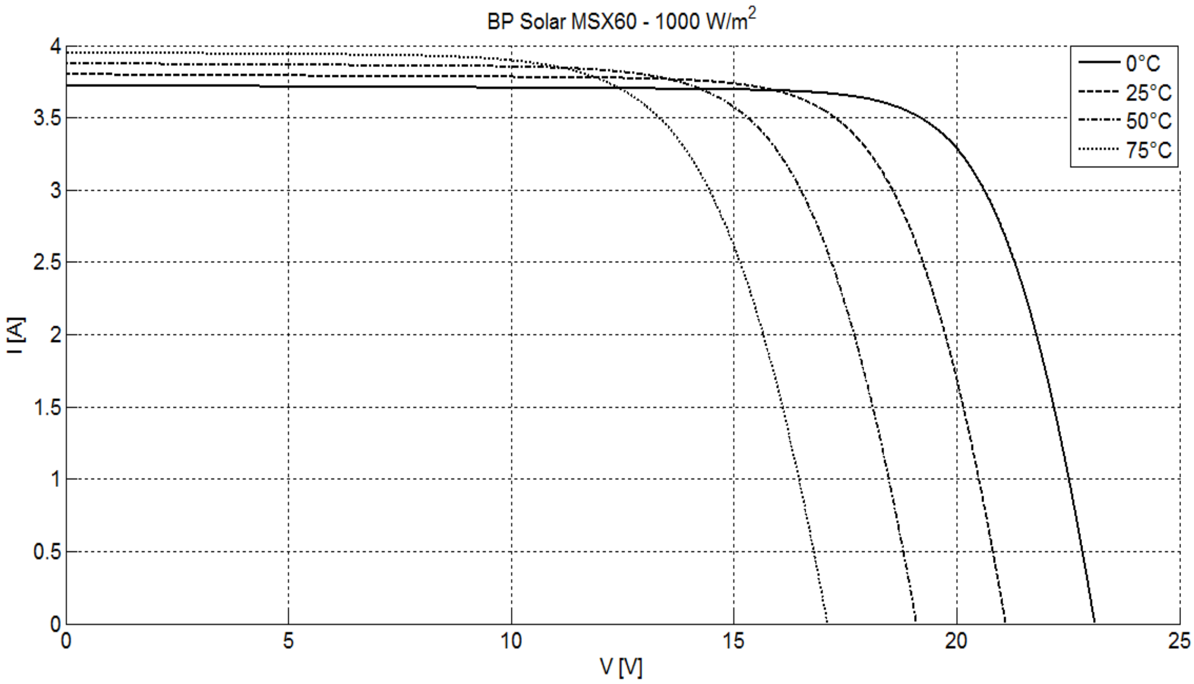
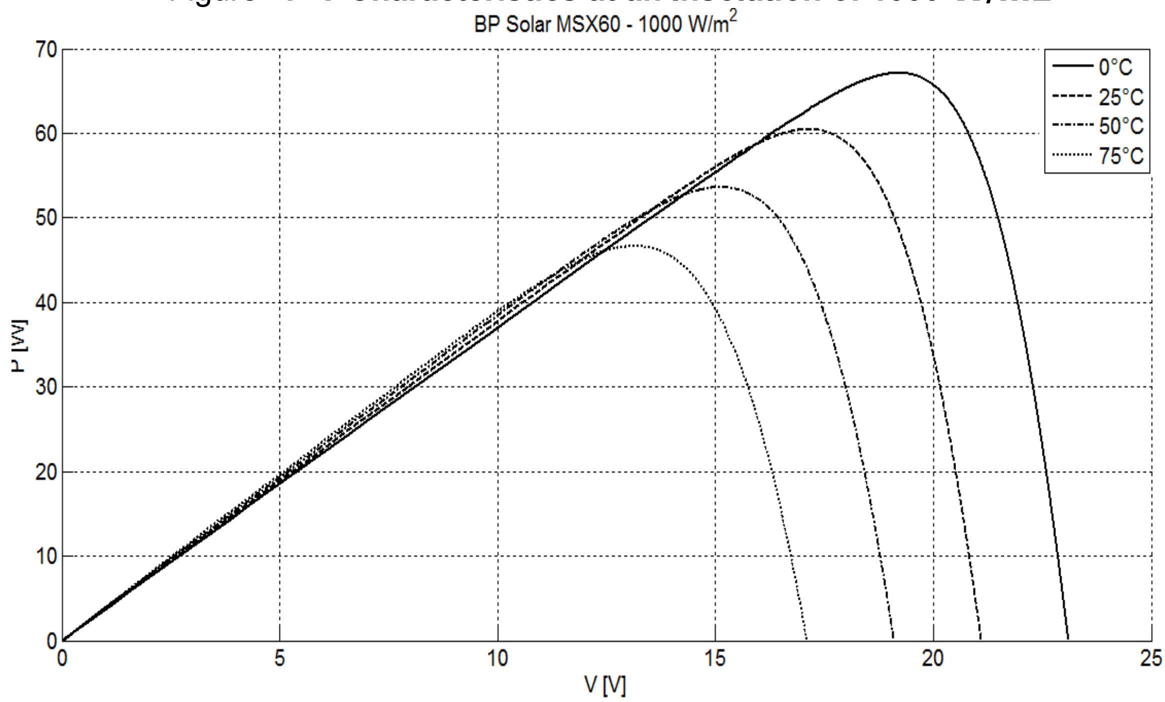
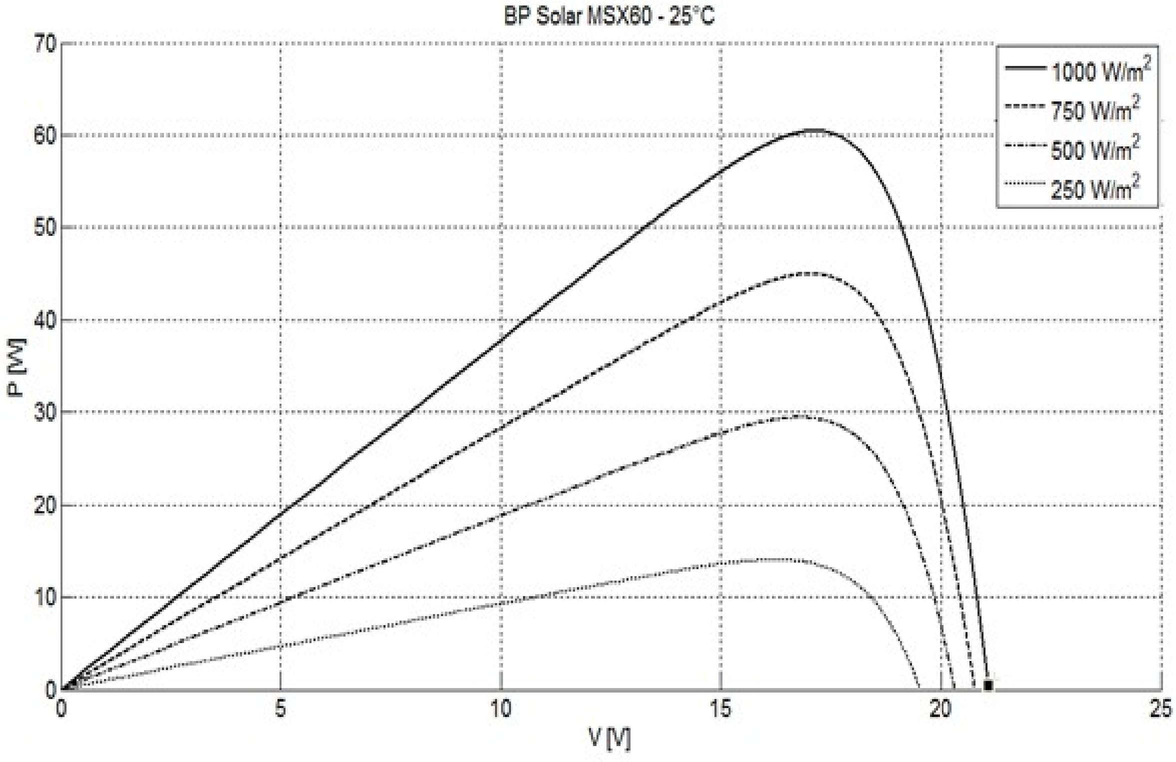



Figure **P-V Characteristics at an Insolation of 1000 W/m2**






V [V]

**Figure** I-V Characteristics at a Temperature of 25°C

**Figure** P-V Characteristics at a Temperature of 25°C

When all the above characteristics have been obtained and analysed, it can be seen that the two diode PV cell provides an appropriate model as compared to other models (Ishaque, Salam & Taheri, 2011; Salam, Ishaque & Taheri, 2010). Due to an extensive research conducted on this model in the past, it was stated that this model produces accurate results at low insolation levels as well as near Voc values, so it will be used in this study. The characteristics in all the figures were displayed using the model equations and the information available in the MSX-60 datasheet (UMAINE, 2011). The I-V and P-V characteristics for the two diode model, along with all the other models are valid. This is due to its comparison with the characteristics displayed in the manufacturer's data sheet, as they are quite similar.

## 3.5 Validating the Model and Important Parameters

The parameters, which need to be determined for the improved and modified model, includes: IS, a, RS and RP. This modified two diode model involves less input parameters and a comparison can be made between the calculated and the experimental values to determine the validity of this procedure. These parameters can be determined by using an analytical technique in which the combination of RS and RP is used to match the experimental and the calculated maximum power (MP) (PMP= VMPIMP) (Ishaque, Salam & Taheri, 2011; Villalva et al., 2009). The initial value of RS is set to zero where as RP is initiated from equation (3.5.1) below.

RP (min)= VMPIsc (STC)– VOC(STC)- VMPIMP ---------------- (**3.5.1**)

RP(min) , is the minimum value of the shunt resistance, VMP is the voltage at MP and IMP is the current at MP. The initial values of both resistances can be used to calculate IS1= IS2= IS from equation (3.4.2) (Page 44). The values of a1and a2 can be chosen at random but can only be between 1 and 2. The three unknown parameters, IS1= IS2, RS and RP are calculated using equation (3.5.2) (Villalva et al., 2009).

PMP = VMPIPV – IS expVMP+IMPRSa1Vt1+ expVMP+IMPRSa2Vt2- 2- VMP+IMPRSRP = PME --------------------------------- (**3.5.2**)

Here PMP is the iteratively calculated MP and PME is the MP obtained from experimental data. The value of RS is slowly incremented using the iteration method until, PMP= PME.

If a mismatch is found, a new value of RP can be calculated using equation (3.5.3) (Villalva et al., 2009).

RP= (VMP+IMPRS)IPV – IS expVMP+IMPRSa1Vt1+ expVMP+IMPRSa2Vt2- 2- PME VMP ----------------- (**3.5.3**)

Figure 37 (Ishaque, Salam & Taheri, 2011; Salam, Ishaque & Taheri, 2010; Villalva et al., 2009) represents the iterative modelling algorithm or the process used to determine/estimate the parameters required to model the modified two diode PV cell. Table 1 (Page 49) shows the values of the original and calculated parameters.

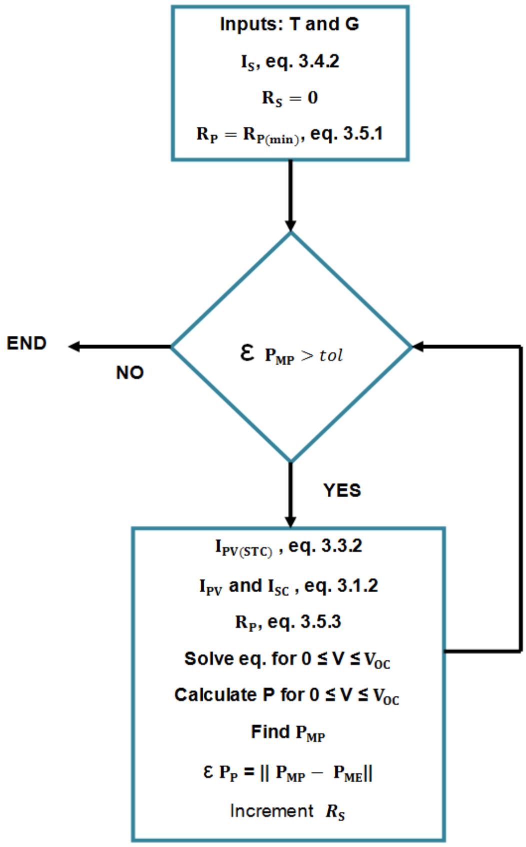
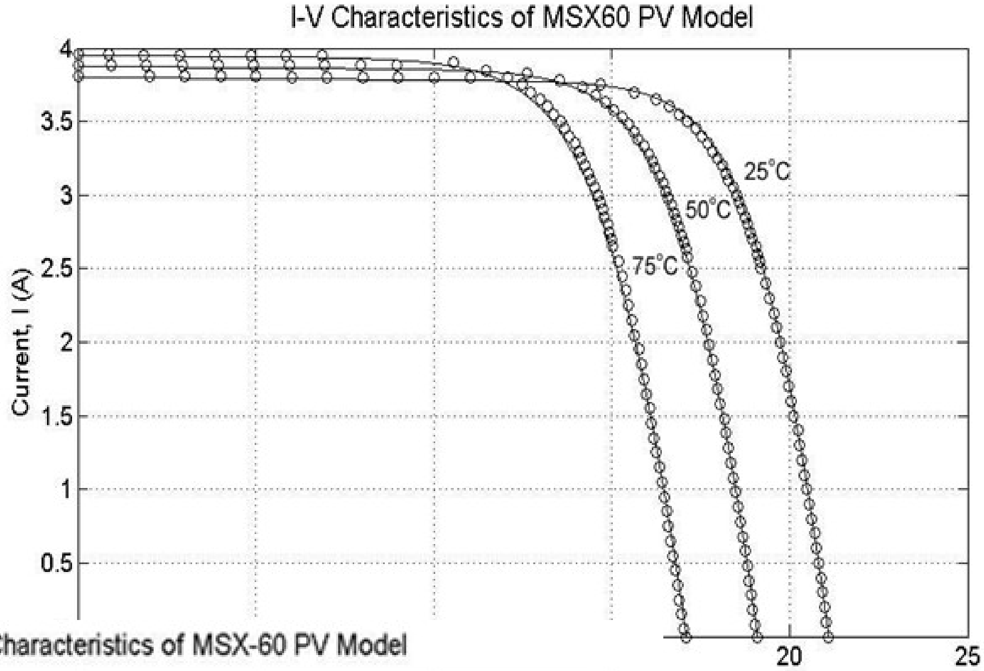


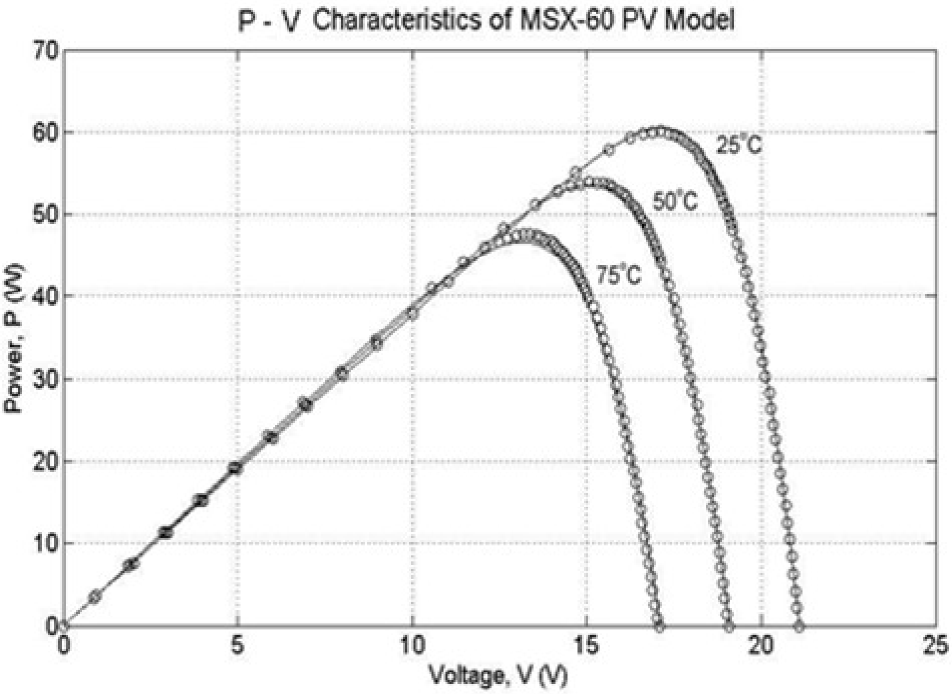

Figure **Iterative Modelling Flowchart**

| | | | |
|---|---|---|---|
| Norma[illegible] | [illegible] | [illegible] | [illegible]arameters |
| Imp | [illegible] | [illegible] | 59.85 |
| Vmp | [illegible] | [illegible] | 5.1e-9 A |
| Pme | [illegible] | [illegible] | 5.1e-8 A |
| Isc | 3.8 A | a1 | 1.6 |
| Voc | 21.1 V | a2 | 1.2 |
| Kv | -80 mV/°C | Rp | 228.18 Ω |
| Ki | 3 mA/°C | Rs | 0.247 Ω |
| Ns | 36 | | |

The I-V (Figure 38) and P-V (Figure 39) characteristics for the modified model are shown at different temperatures, where the insolation is set at 1000 W/m2. The plots display the calculated values as well as the experimental values of PME. These experimental values are represented by the marker “o”.

Table **Parameters for MSX-60**




The I-V and P-V characteristics shown above confirm the validity of the modified two diode model and the analytical technique that was applied to adjust as well as estimate the parameters. The results were also validated while considering the data sheet and the experimental data (Ishaque, Salam & Taheri, 2011; Villalva et al., 2009).

# CHAPTER 4 CONFIGURATION OF A PV ARRAY

## 4.1 The Bypass and Blocking Diodes

A diode is a semiconductor that allows the flow of electric current, but only in one direction, while it blocks the current flowing in the opposite direction. In a modern solar panel circuit, two diodes are integrated for bypassing and blocking purposes (Simpleray, 2011).

The bypass diode is connected in parallel to a PV panel and it helps in diverting the current around the panel. This may be required because the panel is either shaded or not producing any power. A blocking diode however functions in a similar way to a normal diode by blocking the current flowing back to the PV panel and preventing the PV panel from getting damaged. Most PV panels have bypass and blocking diodes installed in them during manufacturing. Figure 40 (Xu et al., 2009) below shows a PV panel model with its bypass and blocking diodes.

## 4.2 Configuration of PV Panels as an Array

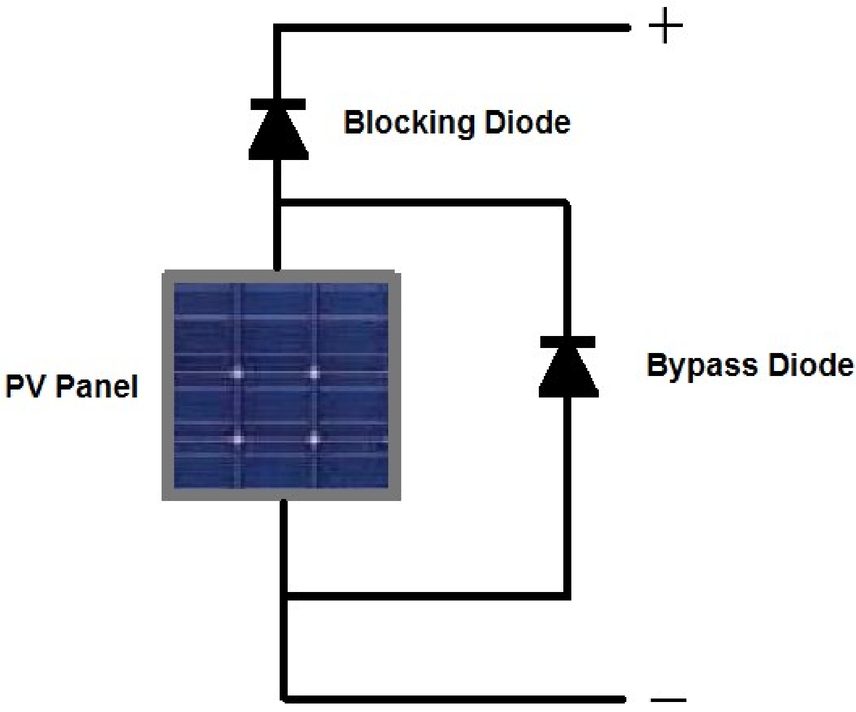
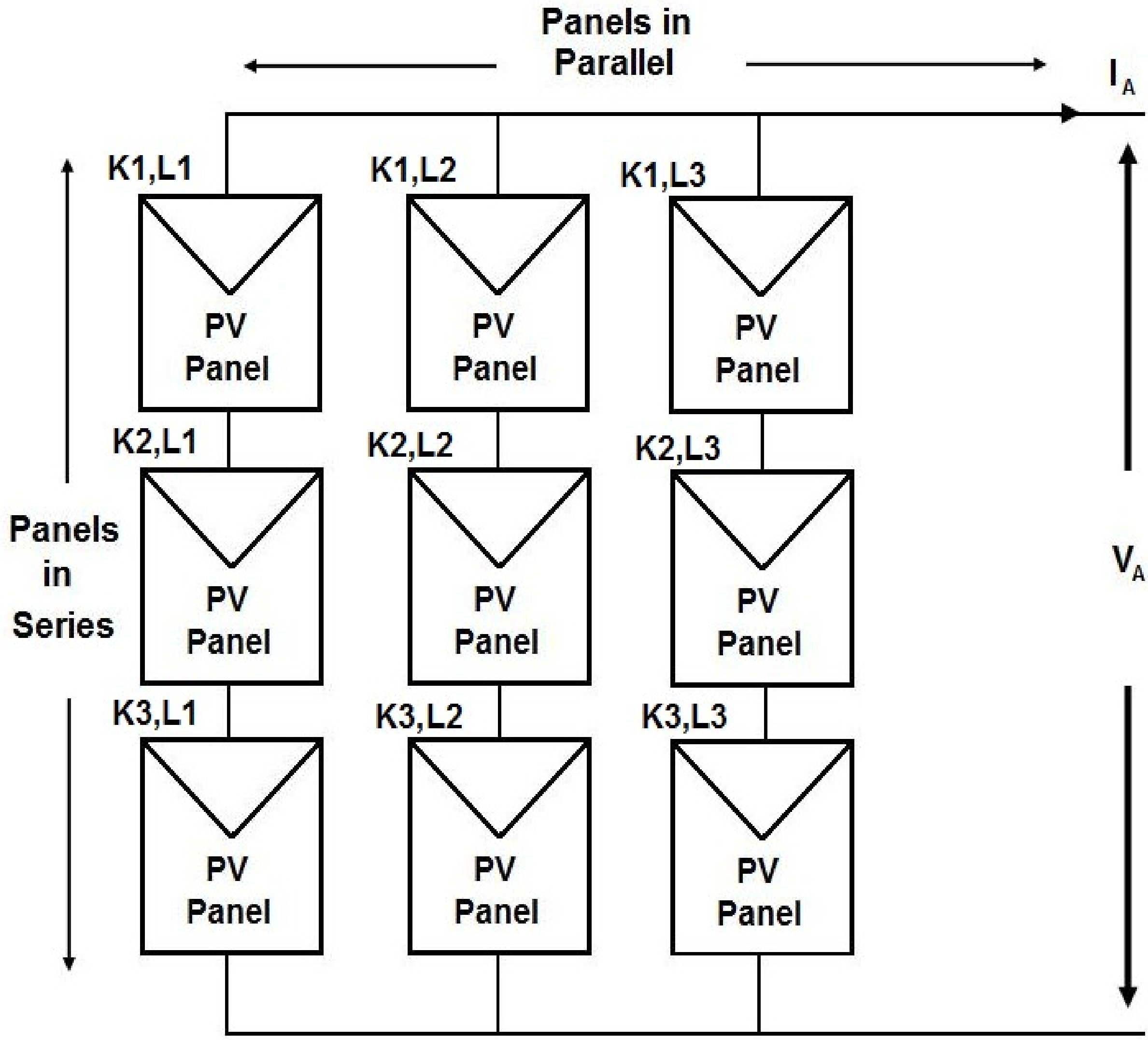


Figure 18 (Page 31), shows that PV panels are constructed by connecting PV cells in different series and parallel configurations. A simple array configuration, used for this study, is shown in Figure 41 below. Here, 9 PV panels (3x3) are connected in series and parallel configurations where VA is the output voltage and IA is the output current of the array.

Figure **PV Array (with Series and Parallel Configurations)**




## 4.3 The Groupings in a PV Array

For a PV Array, equation (3.4.1) (Page 44) must be solved to obtain the voltage that is generated across each PV panel (in an array) at a given current and shading conditions while keeping in mind the other parameters (Ramaprabha & Mathur, 2009). The voltage generated across a PV panel can be represented by VNP and the voltage across a parallel path (in an array) can be represented by $V_P$. The voltage that is across a parallel path "P" can be obtained by summing up $V_{NP}$ for "N" number of panels (Ramaprabha & Mathur, 2009).

$$V_1= V_{11}+ V_{21}+ V_{31}+ \ldots\ldots. + V_{N1}= n=1NV_{n1}$$

$$V_2= V_{12}+ V_{22}+ V_{32}+ \ldots\ldots. + V_{N2}= n=1NV_{n2}$$

$$V_3= V_{13}+ V_{23}+ V_{33}+ \ldots\ldots. + V_{N3}= n=1NV_{n3}$$

- - - - -

$$V_P= V_{1P}+ V_{2P}+ V_{3P}+ \ldots\ldots. + V_{NP}= n=1NV_{nP}$$

As previously discussed, when PV panels are connected in parallel, the output voltage $V_A$ remains constant and equal to the sum of voltages for PV panels connected in series. Also, $I_A$ is equal to the total value of the currents for each PV panel. For this reason $I_A$ can be seen below.

$$I_A= I_1(V_A \le V_1)+ I_2(V_A \le V_2)+ I_3(V_A \le V_3) + \ldots\ldots. + I_P(V_A \le V_P)$$

$$= n=1P\ I_n(V_A \le V_n)$$

Here, the PV array power can be stated as: $P_A= V_A \times I_A$

When PV panels form a very large array, it can be divided into groups of PV panels and parallel paths as seen in Figure 41 (Page 52). If $K_Y$ represents the number of PV panels in a parallel path "P", having the same generated voltage $V_Y$ ($V_Y= V_{NP}$), then "Y" is the group number in that parallel path. For "n" number of groups, the configuration is:

$$V_1= (K_1\times V_{11}) +(K_2\times V_{21})+ (K_3\times V_{31})+ \ldots\ldots. + K_Y\times V_Y$$

$$= n=1YK_n\times V_n$$

Similarly, as shown in Figure 41 (Page 52), if $L_X$ represents the number of parallel paths "P" having the same current $I_X$ ($I_X= I_P$), then "X" is the group number in those parallel paths. For "n" number of groups, the configuration is:

$$I_A= L_1\times I_1(V_A \le V_1)+ L_2\times I_2(V_A \le V_2)+ L_3\times I_3(V_A \le V_3)+ \ldots\ldots.$$

$$+ L_X\times I_X(V_A \le V_X)$$

$$= n=1X\ L_n\times I_n(V_A \le V_n)$$

# CHAPTER 5 IMPLEMENTATION OF THE CODES

## 5.1 Parameters for the Main Module

The code detailed below declares the parameters for PV modelling. The values are taken from Table 1 (Page 49) and the MSX-60 datasheet (UMAINE, 2011). The code was developed in a MATLAB script file and is used as a foundation for the remaining set of codes (Gilat, 2010; Walker, 2005).

```
% msx-60.m            File name
% Parameters          Parameters for MSX-60 PV Panel
Ns = 36;              % Number of PV cells in series [Datasheet]
Isc_T1 = 3.8;         % Short-circuit current at STC [Datasheet]
Voc_T1 = 21.1;        % Open-circuit voltage at STC [Datasheet]
Imp = 3.5;            % Current for MP at STC [Datasheet]
Vmp = 17.1;           % Voltage for MP at STC [Datasheet]
Pmp = Vmp * Imp;      %  MP
Ki = 3e-3;            % Thermal co-efficient of short-circuit current [Datasheet]
Kv = -80e-3;          % Thermal co-efficient of open-circuit voltage [Datasheet]
T1 = 273 + 25;        % STC temperature in Kelvin
A1 = 1.6;             % Ideality factor for D1 [Adjustment]
A2 = 1.2;             % Ideality factor for D2 [Adjustment]
Vt_T1 = k * T1 / q;   % Thermal co-efficient of voltage for a diode at STC [Calculation]
Rs = 0.247;           % Series resistance [Adjustment]
Rp = 228.18;          % Shunt resistance [Adjustment]
q = 1.60217646e-19;   % Electron charge [Standard value]
```

k = 1.3806503e-23;            % Boltzman constant [Standard value]

## 5.2 The PV Model

A MATLAB function has been created in script and named the PV_Model. The purpose for this is to obtain voltage "V" for a PV panel at a specific value of current, sun (insolation) and temperature. The inputs to this function include the current, insolation, temperature and the connected number of PV panels. It calculates the voltage "V" for each case using all the equations listed in the chart and then transfers that to the next function. Figure 42, illustrates the process while the code is detailed in the Appendices.

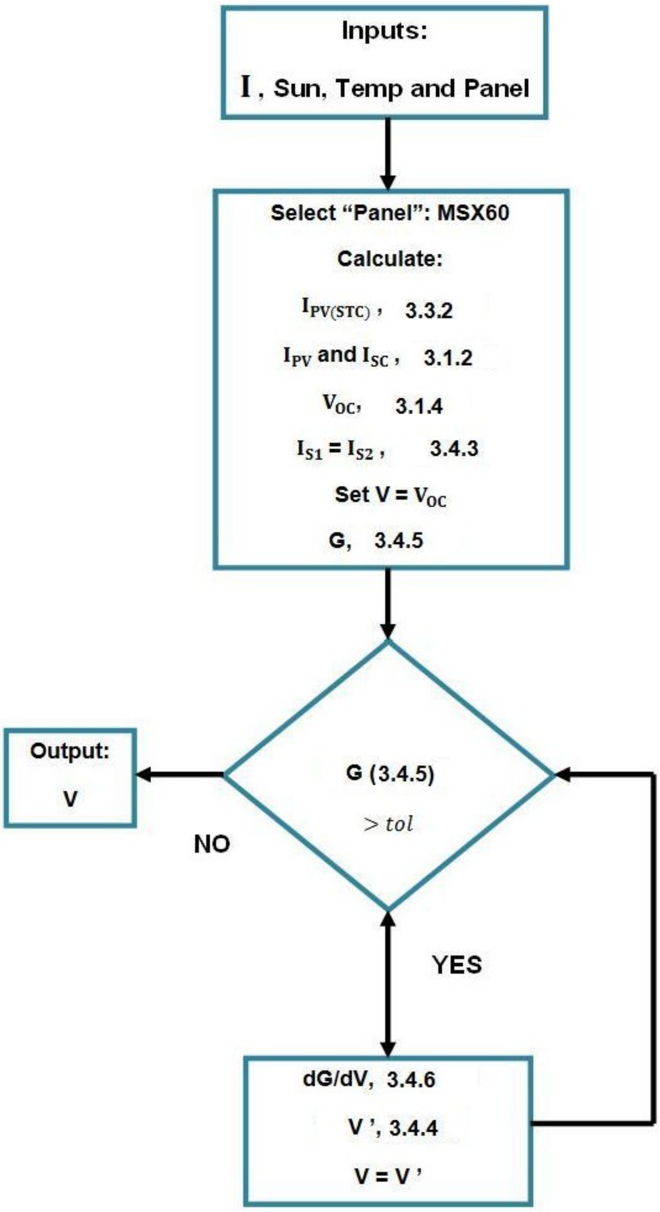



Figure Flowchart for the PV_Model

## 5.3 The PV Panel

This MATLAB function has also been created in script and named the PV_Panel. It helps to acquire the I-V and P-V characteristics for a single PV panel or panels in series and calculates voltage, current and power at a specific value of insolation and temperature. The inputs to this function include the insolation, temperature, number of PV panels connected in series. Figure 43, displays the process while the code is shown in the Appendices (Ishaque, Salam & Taheri, 2011).

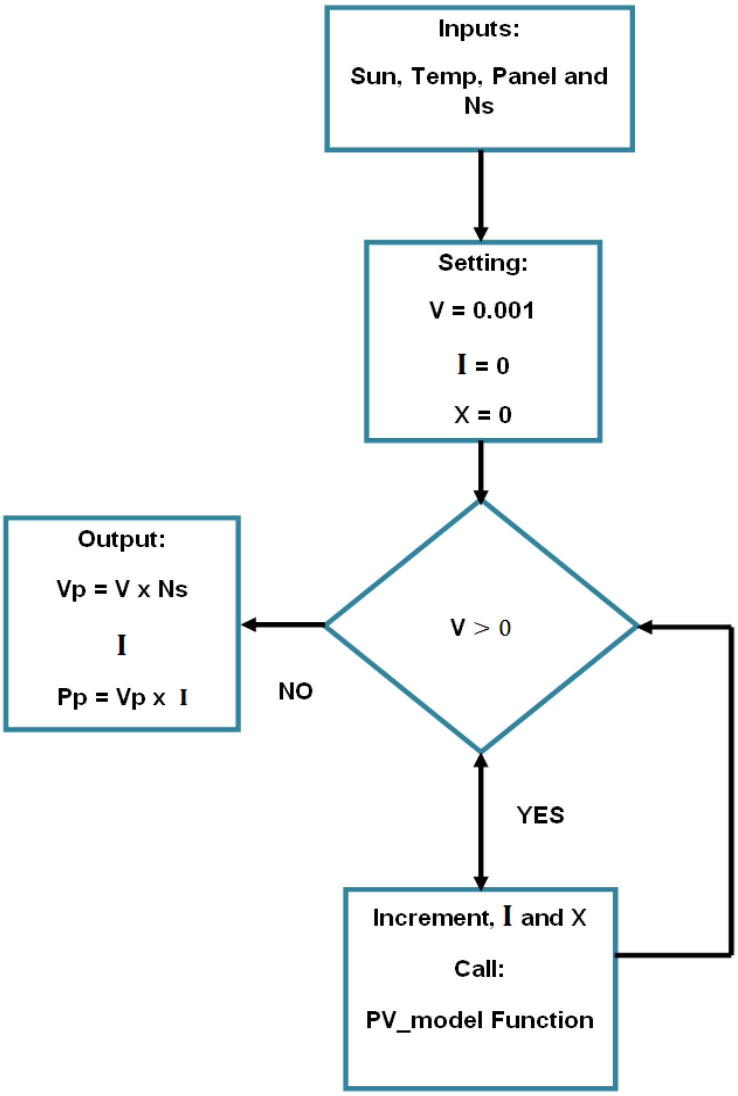



Figure **Flowchart for the PV_Panel**

## 5.4 The PV Group

The MATLAB function has been created in script and named the PV_Group. This helps to acquire the I-V and P-V characteristics of a series and a parallel group of PV panels under different insolation and temperature conditions/values. The inputs to this function include the insolation, temperature, number of PV panels connected in series as well as parallel.

This develops a function for a group of PV panels connected in series but limited to maximum of 3 in a single parallel group. Figure 44 shows this process while the code is included in the Appendices (Ishaque, Salam & Taheri, 2011; Tian, et al., 2012).

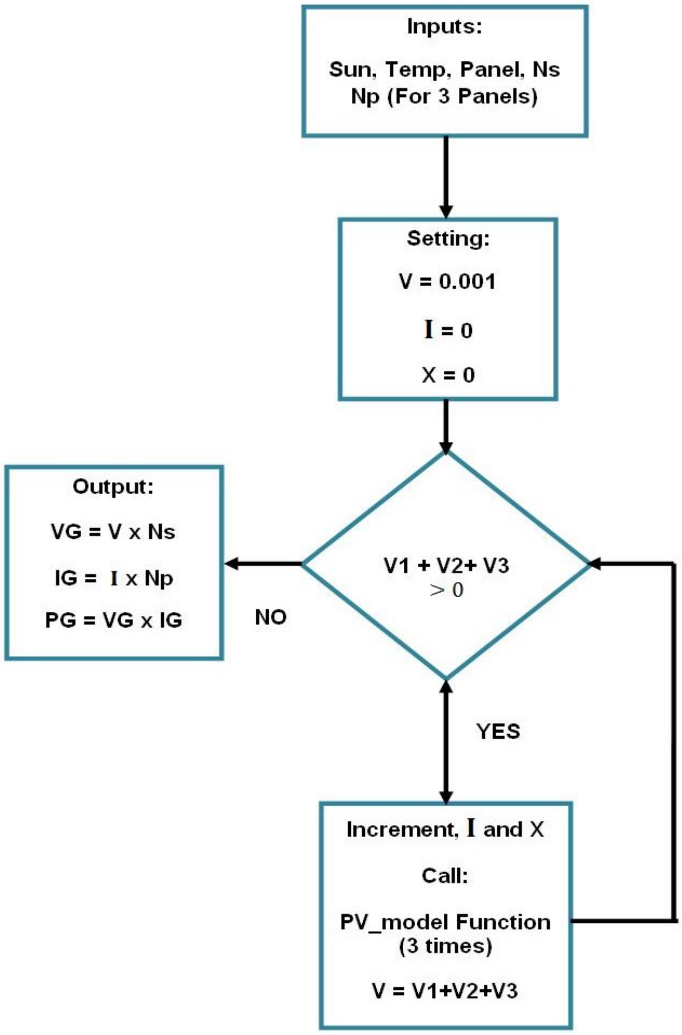



Figure **Flowchart for the PV_Group**

## 5.5 The PV Array

A MATLAB function has not been created for a PV array, instead the previous function PV_Group is used to produce a 3x3 array as shown in Figure 41 (Page 52). This procedure helps to acquire the I-V and P-V characteristics for 3 PV panel parallel groups, each having 3 PV panel groups in series. In total, 9 of these PV panel groups are connected, which are under different values of and temperature. The inputs to this function are the same as “The PV Group” which is also used three times to develop this array. The miscellaneous functions represent: current calculation, organising data, curve estimation, blocking and bypass diodes. Figure 45 displays this process.

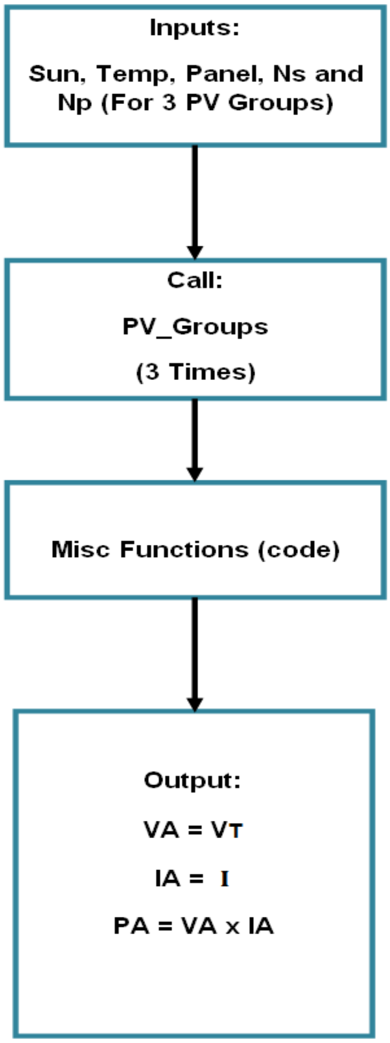



Figure **Flowchart for the PV Array**

# CHAPTER 6 MATLAB-GUI MODEL

## 6.1 Features of the MATLAB-GUI

GUI's can be created by using GUIDE in MATLAB and consist of a figure window containing menus, buttons, text, graphics, plots and much more. There are two main steps in creating a GUI in MATLAB; the first step is to design layouts while the other is to write (MATLAB script) and relate functions with them. These functions perform the desired operations when the user selects different features or components (Hunt et al., 2006; The MathWorks, 2012). When the GUI is run, these functions, known as callbacks, appear automatically for each component as well as for the GUI itself. As these functions are component related, their operation has to be entered as text. An example for this is: what should happen when a button, list box, plot etc. is used.

The MATLAB-GUI setup developed in this case consists of a PV array which is used to study the I-V and P-V characteristics and other effects associated with it. The main features of this GUI are as follows:

- Creating a single PV panel, a parallel and series group of PV panels and then a 3x3 (9 PV Panels groups) PV array;
- This setup consists of text boxes, push buttons, drop down menus and inputs;
- Creating plots for estimating and displaying the I-V and P-V characteristics;
- Displaying the I-V and P-V characteristics of a PV panel, series and parallel groups and finally the PV array;
- Simulating the above under same and different insolation levels, temperatures and shading patterns;
- Simulating the MSX-60 and other commercially available PV modules if required;
- Simulation of the PV array with or without the bypass and blocking diodes.

## 6.2 The PV Array as a GUI

A PV array was developed as a GUI in GUIDE by using built-in components such as text boxes, data input, blocks and push buttons (Hunt et al., 2006). Firstly a PV panel group, Figure 46, was created with input options of insolation, temperature and the number of cells in series.

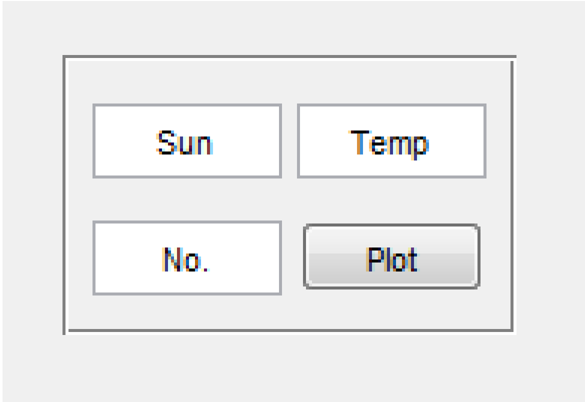


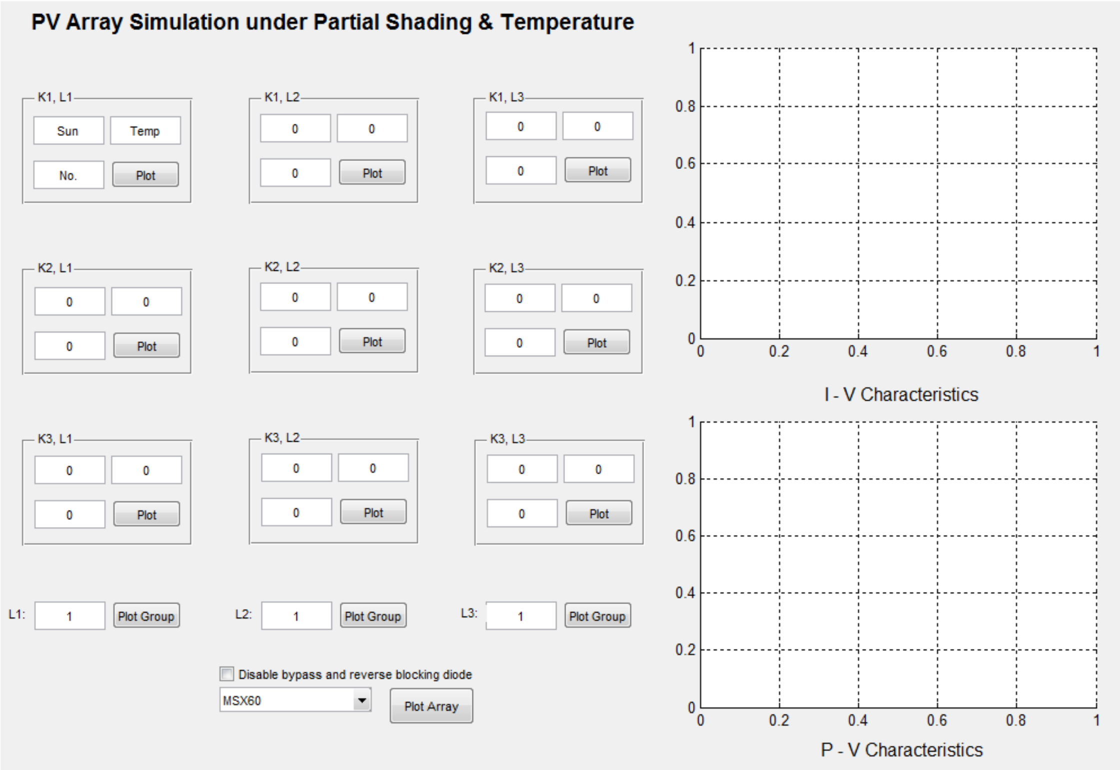

Figure **Single PV Panel Group**

Here the input “Sun” represents the insolation in G/Go format, “Temp” is the temperature in degree Celsius, “No.” is the number of PV panels in series that the group consists of and “Plot” is the push button used for displaying the I-V and P-V characteristics for this PV panel group.

The single PV panel group is used to produce a PV array in a 3x3 configuration similar to Figure 41 (Page 52). This consists of 3 single PV panel groups in series (forming a parallel group) and there are 3 such parallel groups, making a total of 9 (3x3) PV panel groups. If required by the user, this array configuration can be changed to a configuration of 9x9, 12x10, 25x19 etc.

As per the configuration explained above, “K” represents the series group whereas the parallel groups are represented by “L”. Each of the 9 PV panel groups are represented by a format: KxLy. Here, “x” is the number of the series group in a parallel path and “y” is the number of that parallel path. Figure 47, shows the main configuration and the groups together with the plots.

K1L1, represents the first series group in the first parallel path and push button “Plot Group” plots the complete group. Now for example: L1 is one of the 3 parallel groups and if the text box, next to the push button, is edited to “2”,it will show the characteristics of 2 PV groups in parallel. The number of parallel groups can be changed any time by simply editing the text box. The “Disable bypass and reverse blocking diode” is an option to enable or disable the protection diodes. Also, the drop down menu shows the option set as “MSX-60” but more types of PV modules can be added. Finally, the “Plot




Array" push button allows the plotting of a complete array in the display window on the right.

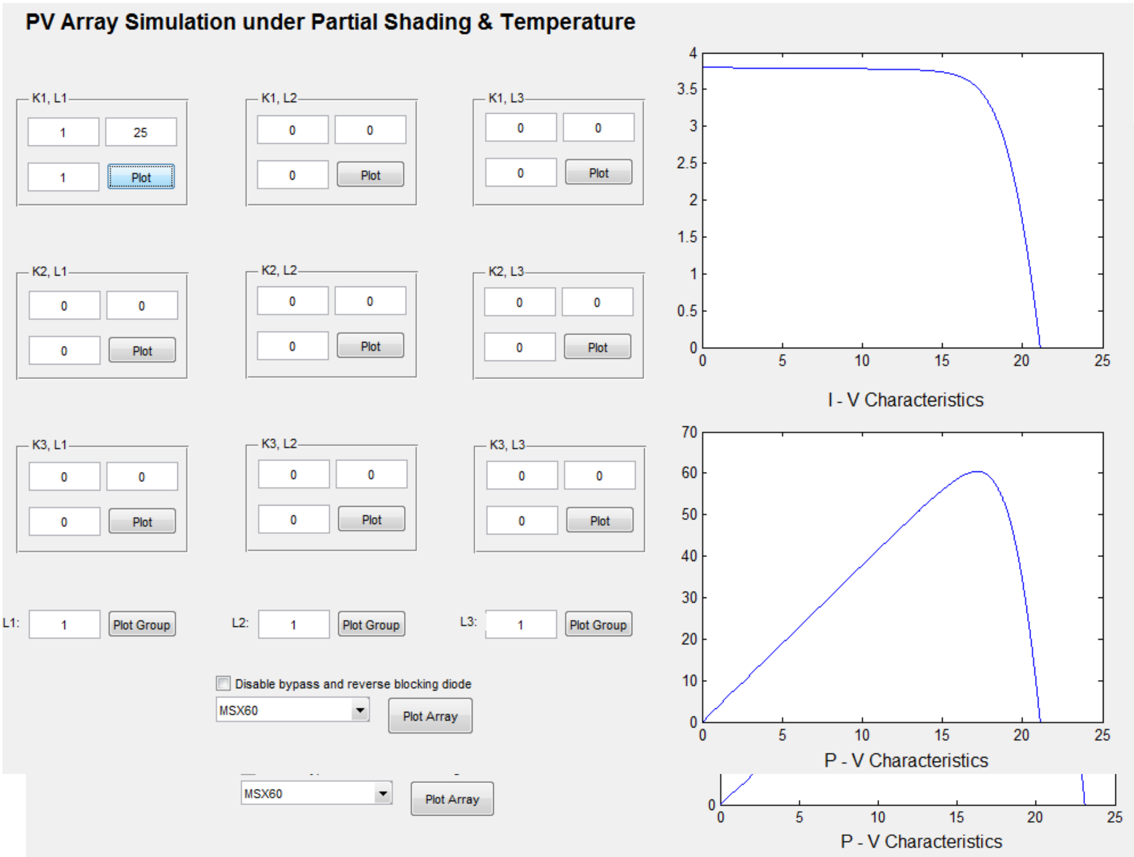
When the GUI model is "RUN" in GUIDE, it generates a code based on all the components, figures, text boxes and other added windows. This code is automatically created and includes call back functions or call backs which need to be modified. The call backs are modified by writing instructions and using the technique to "call" previously saved functions: PV_Model, PV_Panel, PV_Group and PV_Array. At this point, the GUI model is ready to display the characteristics based on the conditions and values entered.

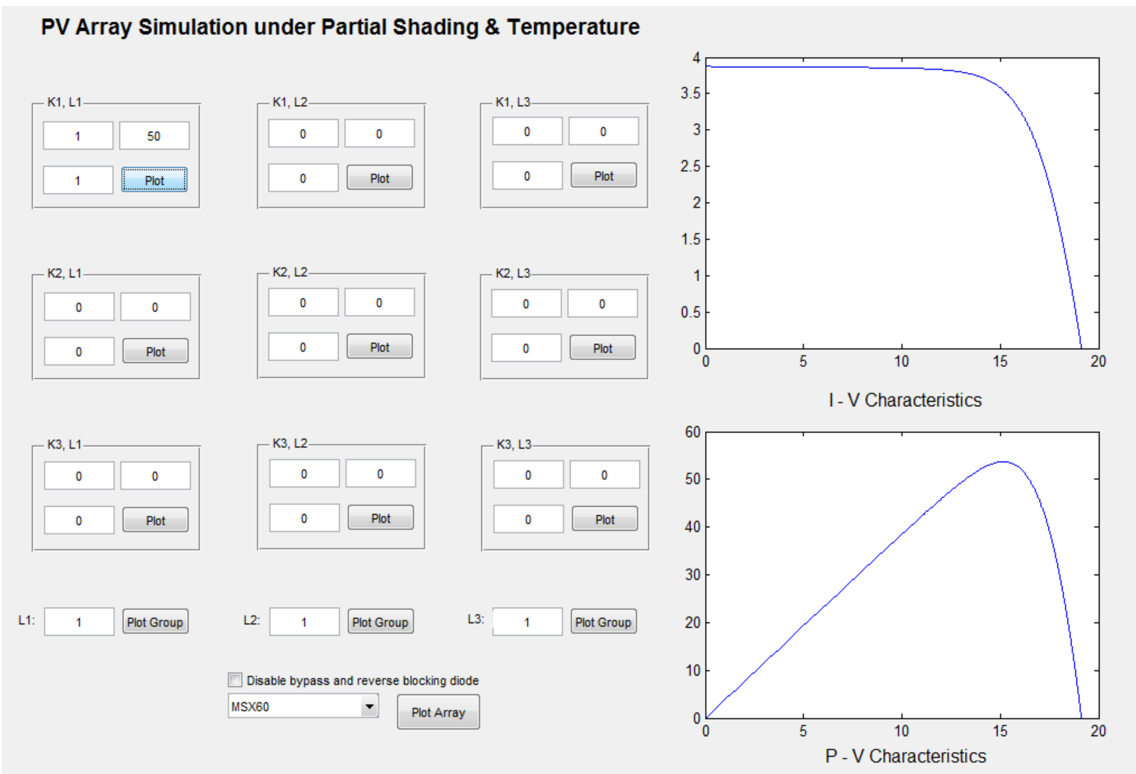
## 6.3 Different Configurations and Varying Conditions

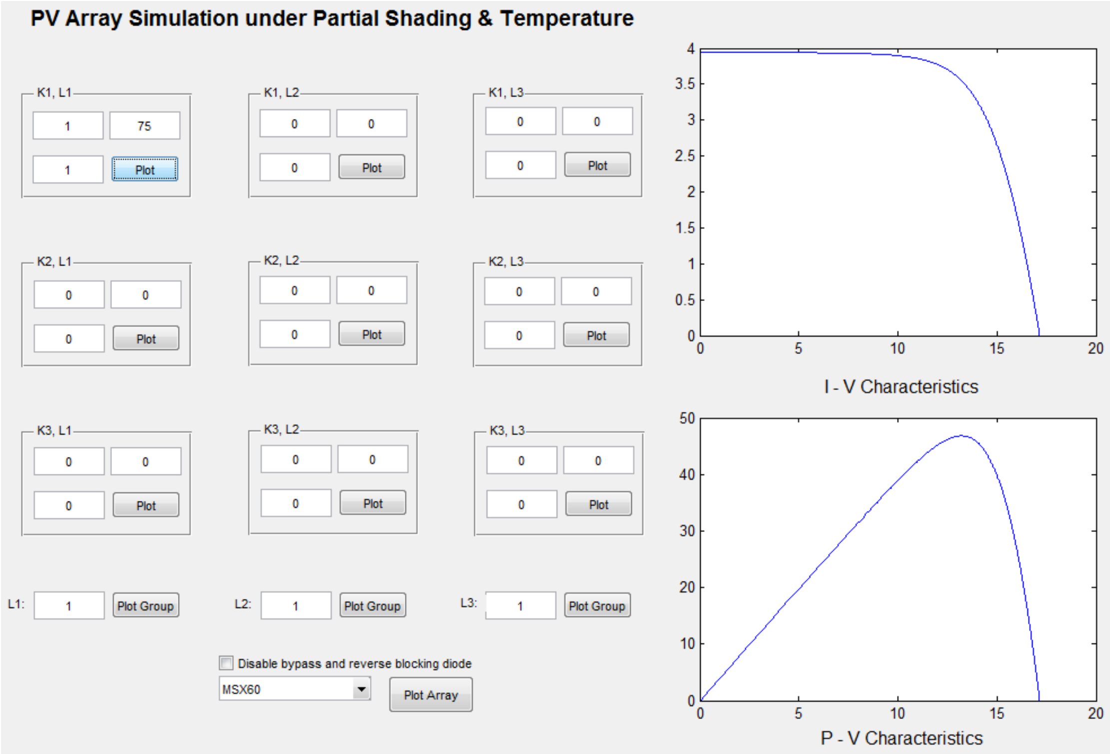
The GUI model can be used to create a scenario of partial shading and varying conditions by modifying insolation levels and/or temperature values. The resulting estimated characteristics can be used to further study these scenarios on PV panels and arrays. The following arrangements show different configurations, under varying conditions and most importantly the I-V and P-V characteristics.

### Setup 1

A single PV panel group can be setup to validate the characteristics and performance of the PV cells, as displayed in the MSX-60 data sheet plus the modified model characteristics ((Ishaque, Salam & Taheri, 2011; UMAINE, 2011). The insolation level is 1 (1000 W/m2), the number of PV panels in series is 1 and the temperature is set to four different values: Setup 1(a) is at 0°C (Figure 48), Setup 1(b) is at 25°C (STC) (Figure 49), Setup 1(c) is at 50°C (Figure 50) whereas Setup 1(d) is at 75°C (Figure 51). The push button, “Plot” was used in all the cases and the characteristics can be seen as follows:






The characteristics that are displayed in this setup are similar to the ones shown in the modified model, which validates the PV GUI model .

## Setup 2

In Setup 2(a), all the STC values are retained from Figure 49 1(b), but now there are 3 single PV panel groups in series and they are all made of a single parallel group. The I-V and P-V characteristics in Figure 52 show that the value of voltage has increased threefold while the value of current remains the same and there is an increase in the overall value of power.

For Setup 2(b), all the STC values have still been retained but now there are 2 parallel groups connected together. The I-V and P-V characteristics in Figure 53 show that the value of voltage remains the same and the value of current has doubled, while the overall value of power has increased further.

The push button “Plot Group” was used for both the cases in order to display the characteristics.

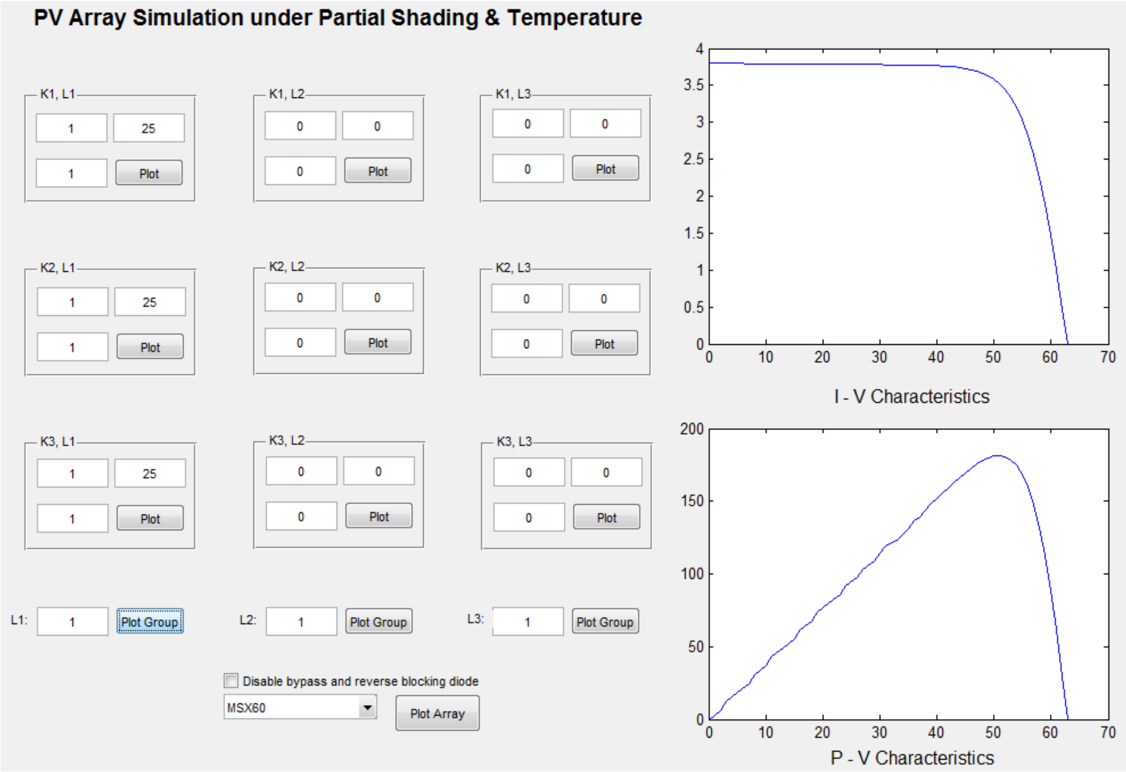



Figure **I-V and P-V Characteristics for Setup 2(a)**

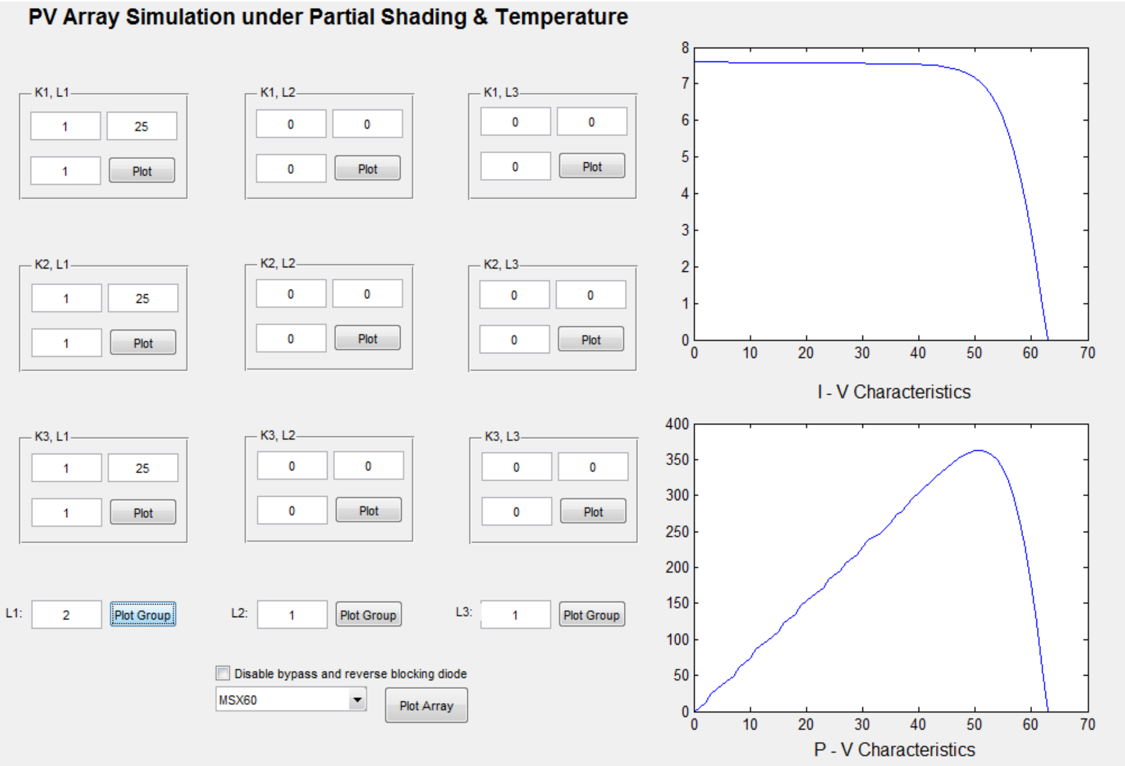



Figure **I-V and P-V Characteristics for Setup 2(b)**

## Setup 3

In Setup 3(a), a single PV panel group is set at varying conditions; the insolation level is 0.6, temperature is set to 18°C and the number of PV panels in series is 1. The push button “Plot” was used and the resulting characteristics can be seen in Figure 54. When comparing it to the characteristics for STC values, the reduction in the insolation and temperature has reduced the value of current and power but the value of voltage is almost the same.

Now for Setup 3(b), all the values have been retained but the groups are similar to Setup 2(a). The push button “Plot Group” was used and the results can be seen in Figure 55.

Setup 3(c), is similar to Setup 2(b) apart from the insolation and temperature values. The results therefore follow the same trend but provide different output values as seen in Figure 56. The push button “Plot Group” was also used for this case in order to display the characteristics.

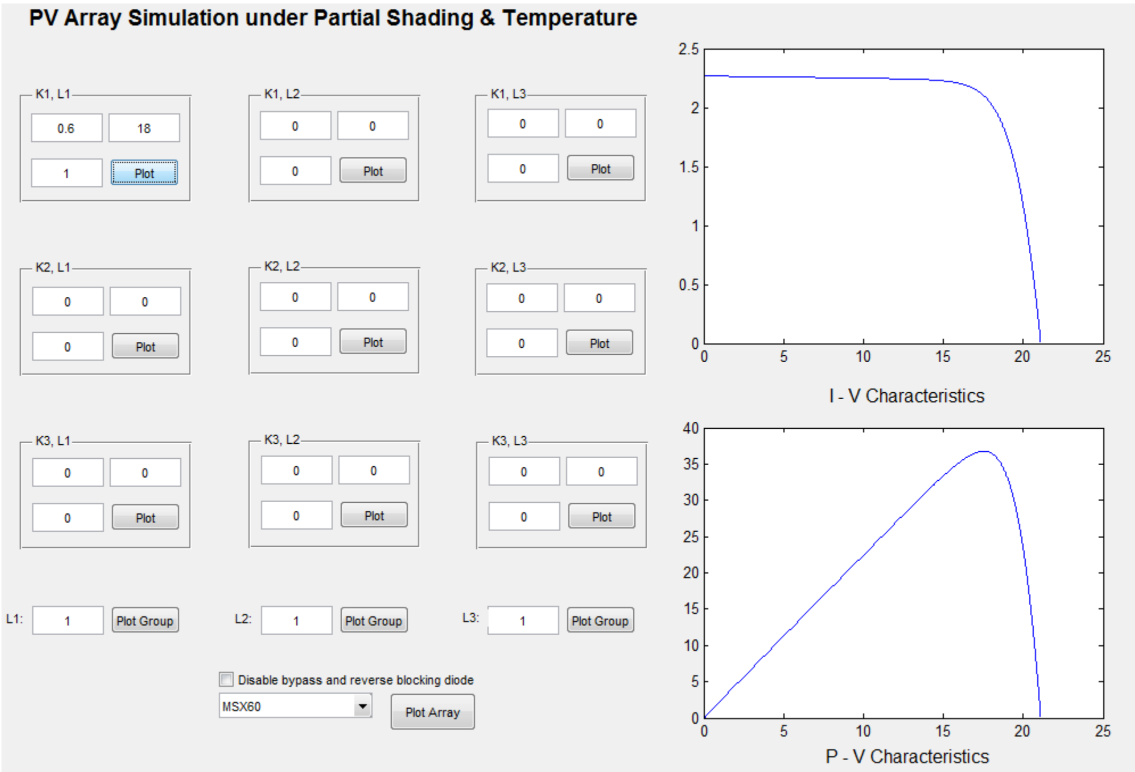
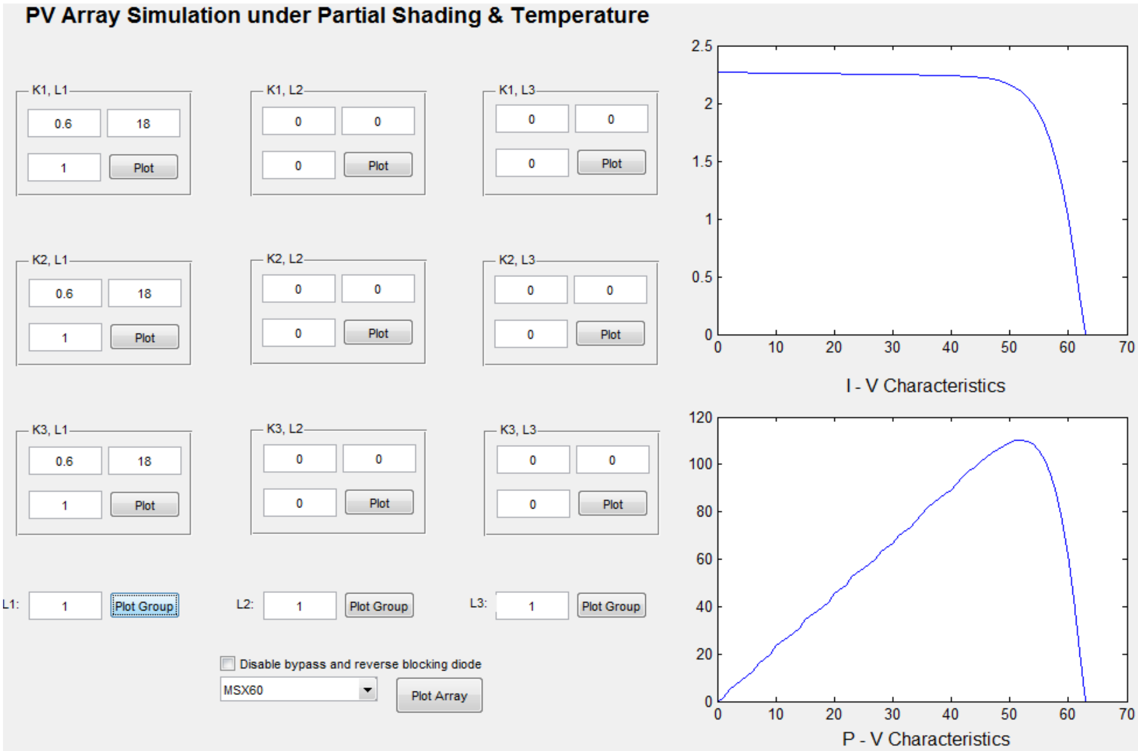
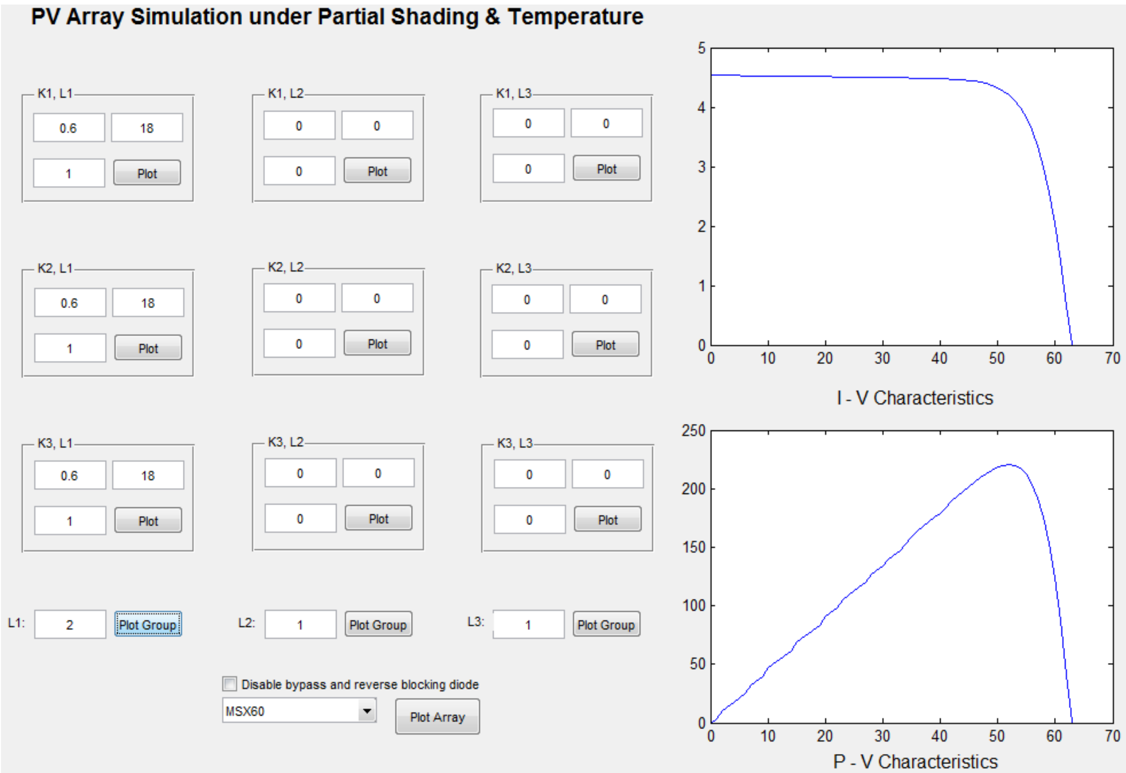



Figure **I-V and P-V Characteristics for Setup 3(a)**



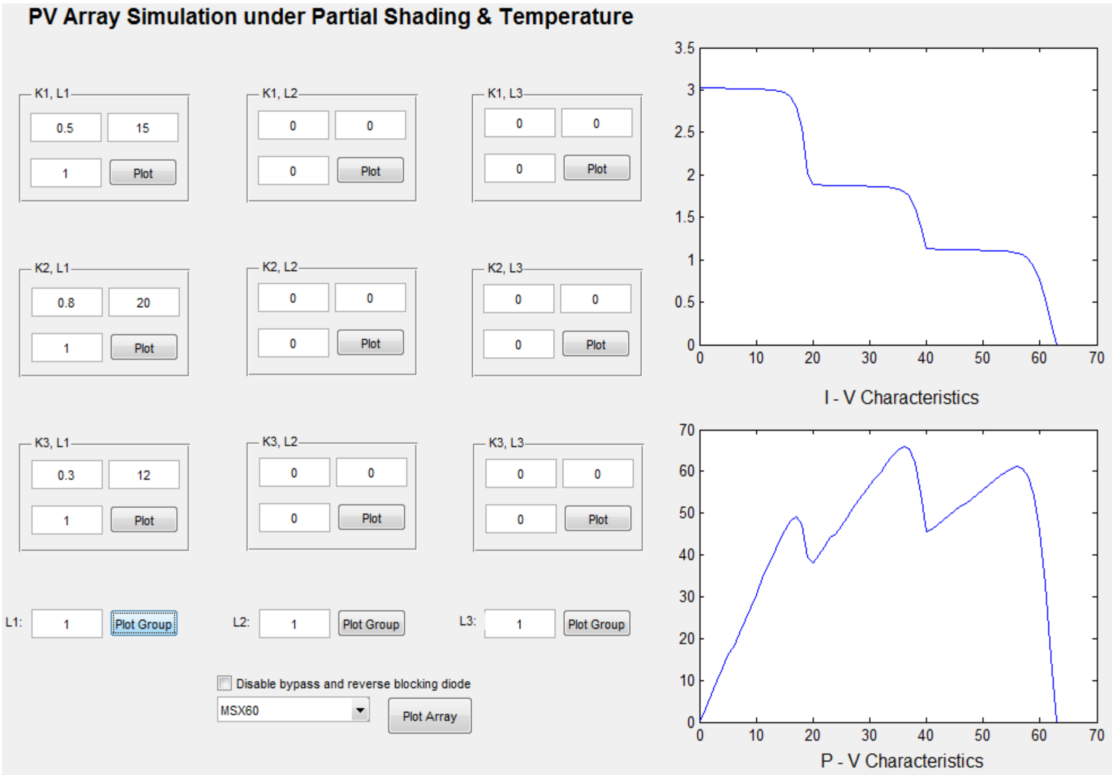



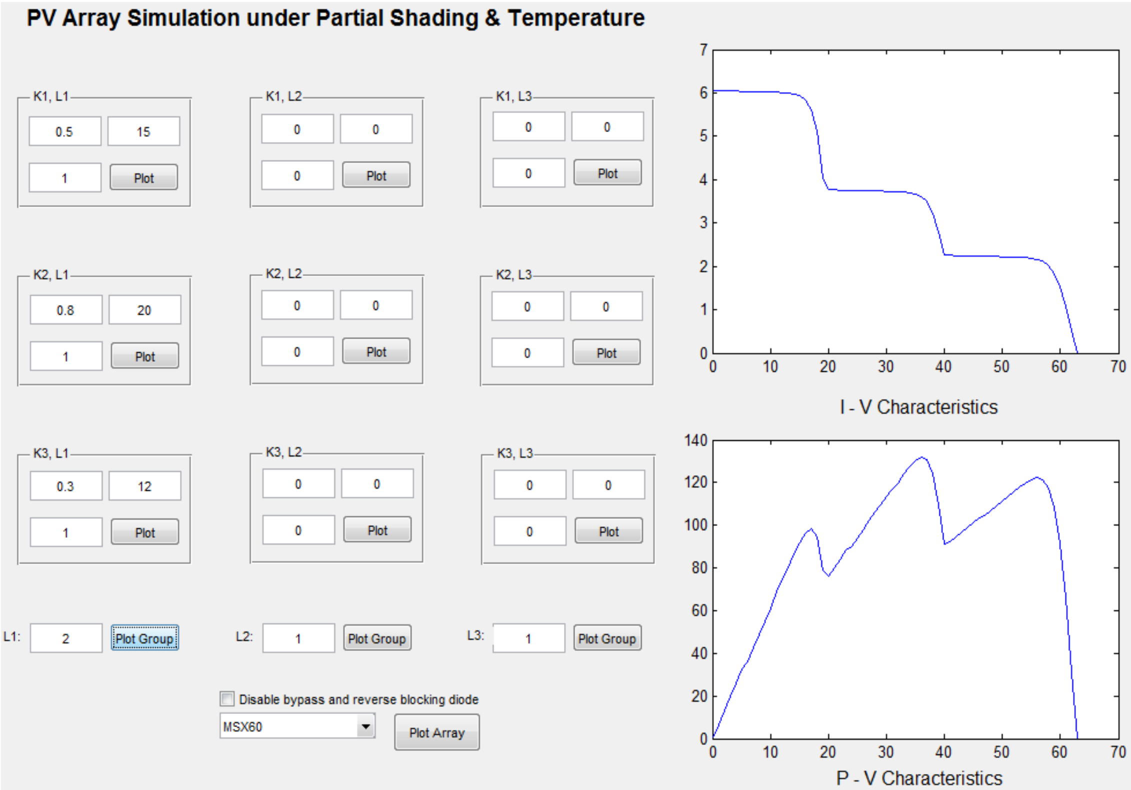

## Setup 4

For Setup 4(a), a total of 3 PV panel groups are considered in series (1 parallel group) and have varying insolation and temperature values. The characteristics can be seen in Figure 57, where the visible peaks represent distortions due to the different inputs of insolation and temperature. There are three values of MPP; two are local and one of them is global.

In Setup 4(b), the values are again retained but now there are 2 parallel groups connected together instead of 1. The I-V and P-V characteristics in Figure 58 show that the value of voltage almost stays the same but the value of current and overall power has increased.

The push button "Plot Group" was used for both these cases in order to display the characteristics.






## Setup 5

Now for Setup 5, a complete PV array is used where the PV panel groups are connected in a configuration of 3x3. The value of insolation is 0.8, the temperature is set to 20°C and the number of PV panels in series is 1. These values are kept constant throughout the array.

The I-V and the P-V characteristics are displayed in Figure 59. The plots clearly show that there are no peaks present within the characteristics as the conditions are constant. The values of current, voltage and power can be observed for detailed results.

Due to different settings, push button “Plot Array” was used for this case in order to display the characteristics.

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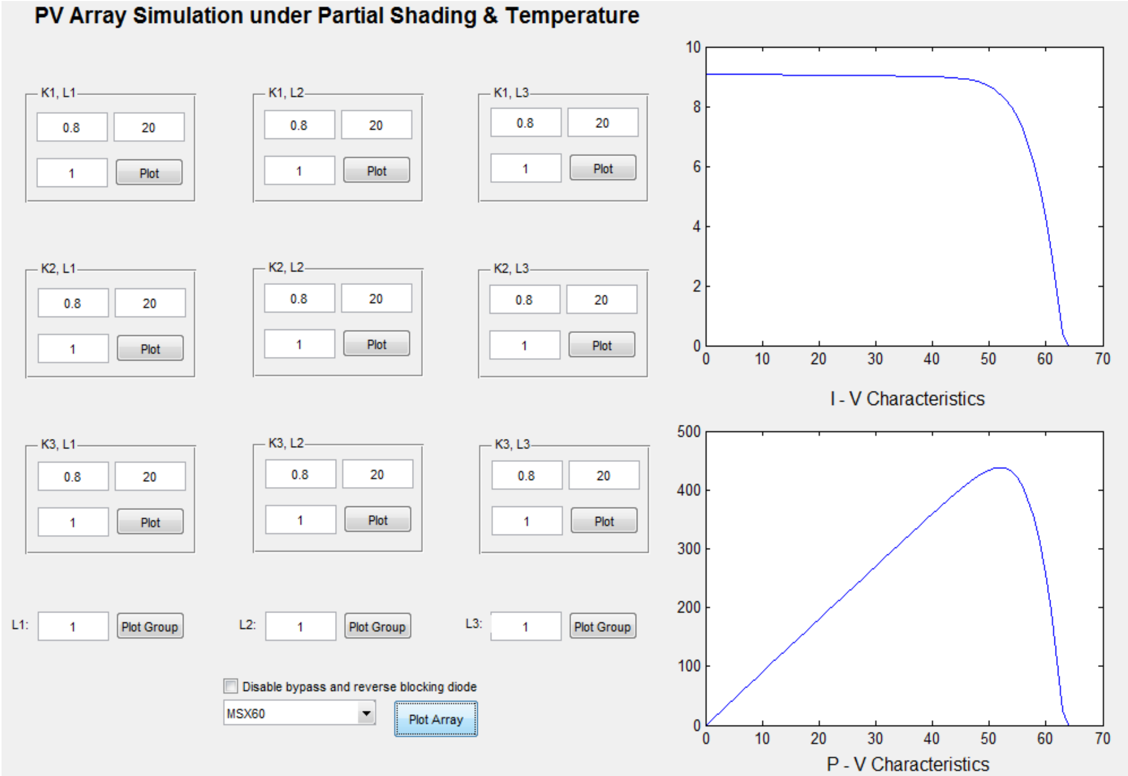



Figure **I-V and P-V Characteristics for Setup 5**

## Setup 6

For Setup 6, a complete PV array is again used with the same configuration as Setup 5. In this case however 7 out of the 9 PV panel groups have same values of insolation and temperature. The purpose of this setup is to display the characteristics of a PV array under partial shading and complete shading for certain PV groups. The 2 remaining PV panel groups are completely shaded so their insolation value is 0, while their temperature is set to 5°C.

The I-V and the P-V characteristics can be seen in Figure 60 and the presence of multi-peaks was observed. The multiple peaks are present in the plots due to partial shading and reduced values of power as well as the MPP. The push button “Plot Array” was also used for this case in order to display the characteristics.

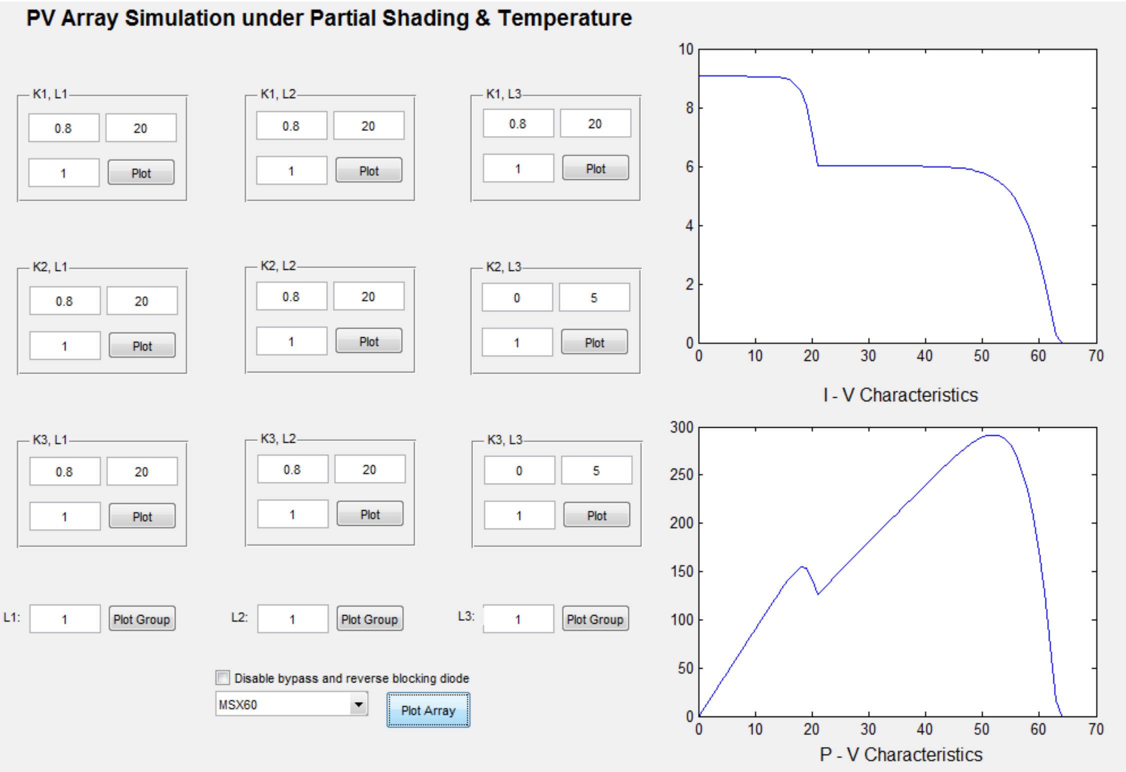


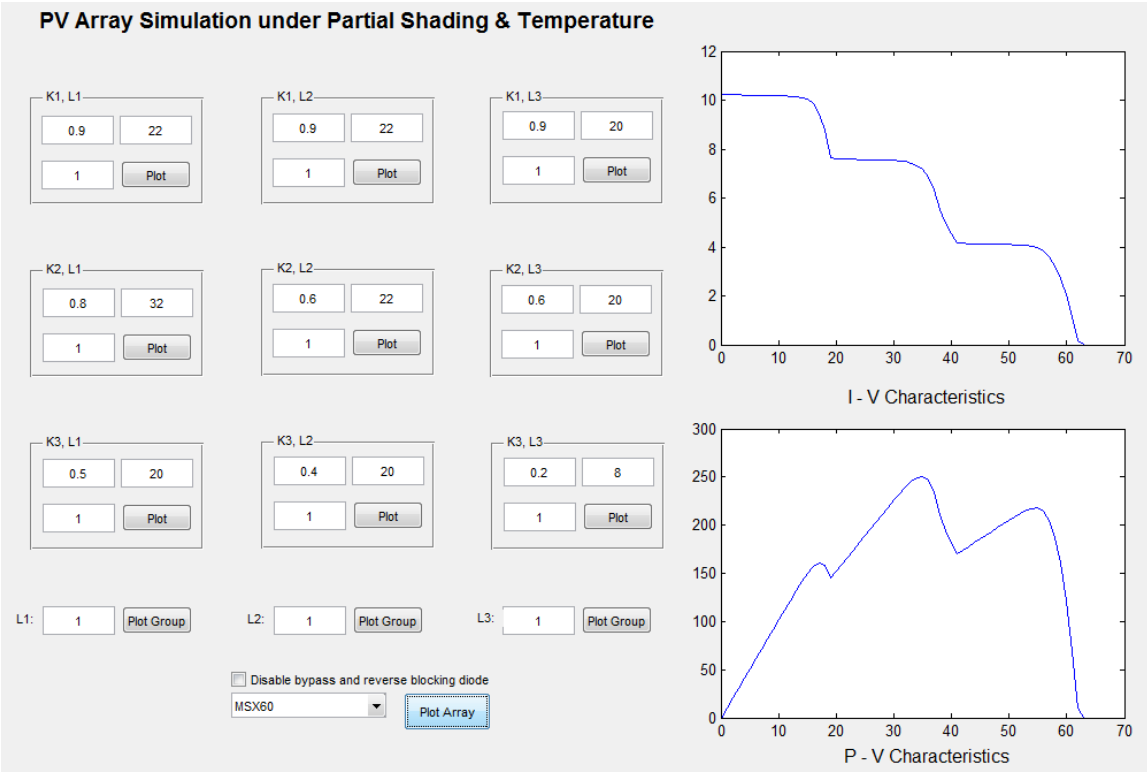

Figure **I-V and P-V Characteristics for Setup 6**

## Setup 7

In Setup 7, a complete PV array is again used as a 3x3 configuration. Here, all the PV groups have different/varying values of insolation and temperature. The aim of this setup is to display characteristics under partial shading and varying external conditions.

The I-V and the P-V characteristics can be seen in Figure 61 and the presence of multi-peaks was still observed. These multiple peaks are present in the characteristics due to the effects of partial shading and varying conditions. It was also observed that the value of power and the global MPP reduced further when compared with Setup 5 and Setup 6.

The push button “Plot Array” was again used in order to display the characteristics.




## Setup 8

As previously stated, the PV array configuration can be modified at anytime, and for Setup 8, a configuration of 10x15 is used. In this setup, 10 PV panels are connected in series and there are 15 such parallel groups bringing the total number of PV panels to 150. The partial shading conditions and the temperatures are retained from Setup 7 while the necessary changes have been made. The I-V and P-V characteristics are presented in Figure 62.

The performance of the PV array was compared with Setup 7 and it was noted that the number of peaks increased due to the inclusion of more panels/groups. Simultaneously, the global MPP also increased due to higher values of current and voltage.

The push button “Plot Array” was used in order to display the final characteristics.

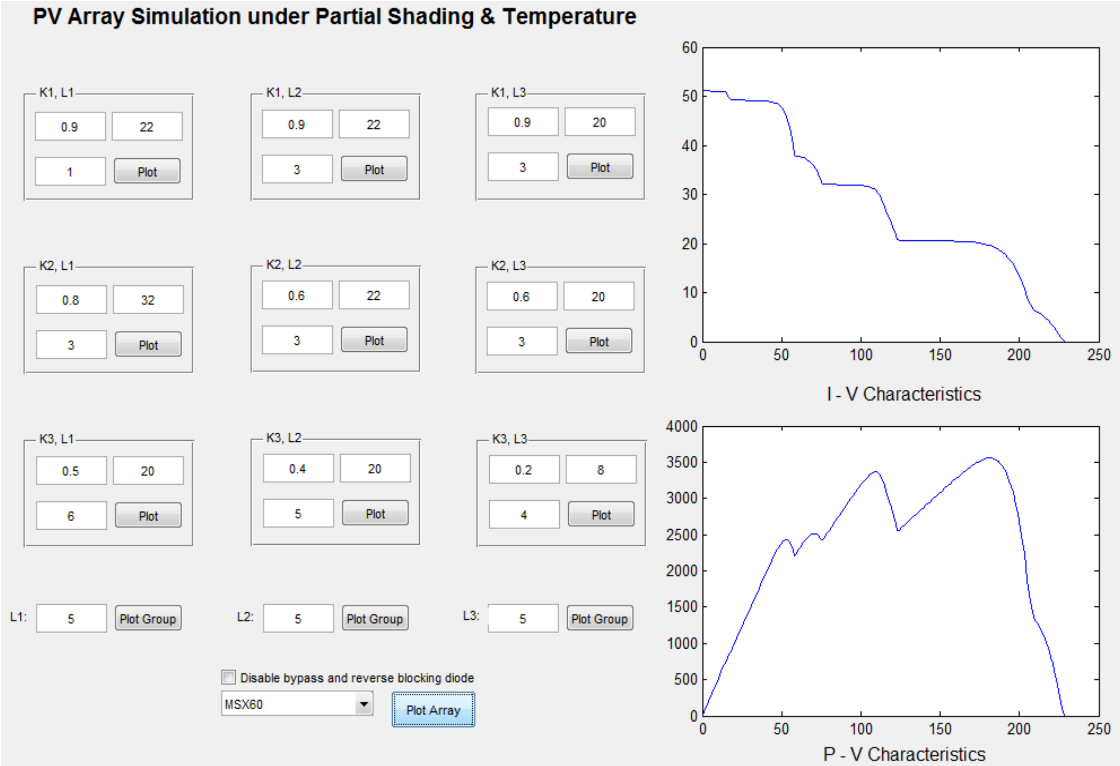



**Figure** I-V and P-V Characteristics for Setup 8

The above simulations show results for different configurations, varying insolation levels and temperatures. Here, when compared with the MSX-60 data sheet, the validity of the estimated I-V and P-V characteristics was also confirmed. When these estimated results and the corresponding accurate characteristics were considered, the efficiency of the two diode model as a GUI can be validated.

Another set of results displayed the accuracy and validity of these estimated characteristics. These results were the expected output values of current, voltage and power; when various combinations of series and/or parallel PV cells/panels were selected.

# CHAPTER 7 CONCLUSIONS AND FUTURE WORK

The aim of this study was to develop and validate a generalised system model of a PV array in order to investigate the effect/s of partial shading and varying conditions on its characteristics. A model of the two diode PV cell was developed, modified and then implemented in a PV array setup using the GUI in MATLAB. The validity of all the PV cell models, especially the two diode model, was determined by direct comparison with the characteristics available in the MSX-60 data sheet. Due to its well known accurate readings at low insolation (partial shading) and near open circuit voltage, the two diode model was used. The accuracy of the modified two diode model was verified from data provided by manufacturers and previous researchers.

For the PV array, which was developed as a GUI, several simulations were conducted under different configurations, varying insolation levels and temperatures. Satisfactory results from these simulations were achieved and the process validates the performance of a PV array under STC, partial shading and varying conditions due to the comparison with the MSX-60 data sheet. In addition, due to the overall performance of the PV panels/array, the effect of series and/or parallel combinations was also validated. The I-V and P-V characteristics clearly show that multiple MPP’s/peaks were obtained under partial shading conditions. These multiple MPP’s/peaks increased due to the increase in the shading patterns. This can be clearly seen, especially in the characteristics for Figure 61 (Page 73) and Figure 62 (Page 74). Here, most of the shading on the PV array was kept constant at first and then it was varied throughout the PV array. The power losses and the complexities in the characteristics were observed due to partial and/or complete shading and varying or constant temperatures.

In future, further research can be carried out to improve accuracies within the actual or the modified PV cell model. Also, other commercially available PV modules can be modelled and partial shading can be implemented by using this method. Finally, an MPPT system can be developed and applied in MATLAB in order to study the tracking of MP under partial shading as well as other varying conditions.

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# APPENDICES

# Appendix 1 PV Model

```
% For PV_Model
% Calculates PV panel voltage at a given current, temperature, insolation
% This is for a specific commercial panel.

function Vc = pv_model2(I, Sun, Temp, Panel, nxt)

k = 1.3806503e-23;
q = 1.60217646e-19;

switch lower(Panel)                       % Will select the PV module configuration file
   case 'msx60'                           % Option for future purposes
           msx60_2
   case 'sp70'
           sp70_2
   case 'sq150pc'
           sq150pc_2
    case 'kg200gt'
           kg200gt_2
   otherwise
    disp('Unknown method.')
end

Tc = 273 + Temp;                          % Calculates the given temperature in Kelvin

Vt_Tc = k * Tc / q;                       % Thermal co-efficient of the diode
                                           % at a given temperature

Ipv_T1 = (Rs + Rp) / Rp * Isc_T1;         % Photo Voltaic current generated at
                                           % STC 3.3.2

Ipv = (Ipv_T1 + Ki * (Tc - T1)) * Sun;    % Photo Voltaic current generated
                                          % at given temp + insolation
                                           % 3.1.2

Isc_Tc = (Isc_T1 + Ki * (Tc - T1)) * Sun; % Short circuit current at given
                                           % temp 3.3.2

Voc_Tc = Voc_T1 + (Kv * (Tc - T1));       % Open circuit voltage at a given temp
                                           % 3.1.4

Irs_Tc = (Ipv_T1-Voc_Tc/(Rp))/(exp(Voc_Tc/(Ns*A1*Vt_Tc))
          + 10*exp(Voc_Tc/(Ns*A2*Vt_Tc)) - 11);
                                           % Reverse saturation current at given temp
                                           % 3.4.3. Note that Is2 = 10 * Is1

% A Routine for fast numerical calculation
if (nxt==0)
    V = Voc_T1;
else
    V = nxt;
end

% Newton Raphson Numerical Solution
g = Ipv-Irs_Tc*(exp((V+I*Rs)/(Ns*A1*Vt_Tc))+10*exp((V+I*Rs)/(Ns*A2*Vt_Tc))-11)-
(V+I*Rs)/Rp-I;                            % Calculation of g is from 3.4.5

% Iteration is done until solution 0.001. Accuracy can be increased at the
```

```
% expense of the resource
while (abs(g) > 0.001)
g=Ipv-Irs_Tc*(exp((V+I*Rs)/(Ns*A1*Vt_Tc))+10*exp((V+I*Rs)/(Ns*A2*Vt_Tc))-11)-(V+I*Rs)/Rp-
I;

dg=Irs_Tc*(1/(Ns*A1*Vt_Tc)*exp((V+I*Rs)/(Ns*A1*Vt_Tc))+10/(Ns*A2*Vt_Tc)*exp((V+I*Rs)/
(Ns*A2*Vt_Tc)))-1/Rp;                          % Derivative value calculation 3.4.6

V_ = V - g/dg;                                  % Newton Raphson 3.4.4

V = V_;                                              % Setting new value
end

if ( V < 0)
   V = 0;
end


Vc = V;                                         % The output Vc
```

# Appendix 2  PV Panel

```
% For PV_Panel
% Calculates the I-V and P-V characteristics for PV panels connected in series
% numb: Is the number of PV panels connected in series

function [Volt, Cur, Pwr] = pv_panel2(numb, temp, sun, panel)

% setting the initial values
I = 0;
x = 0;
V = 0.001;

% Increasing current so voltage drops, until it becomes zero
while(V > 0)
   I = I + 0.001;                                   % Incrementing


   x = x + 1;

% Routine for faster numerical calculation
   if (x<=1)
      nxt = 0;                                      % Initially set to zero,
                                                     % Open circuit voltage
   else
      nxt=Volt(x-1)/numb;                           % or set to previous voltage
   end


 V = pv_model2(I, sun, temp, panel, nxt);          % Call the PV model function to
                                                     % calculate the voltage

% If the voltage deviation is greater. Then reduce the current to get a better
% value of the voltage
  if (x>2)
dev_V = Vsum_last - V;                              % Value difference
 if (dev_V>4)                                       % Checking if the value
                                                     % difference is > 4?
```

```
I = I - 0.0009975;                                  % If so then Reduce
                                                     % Current again
V = pv_model2 (I, sun, temp, panel,nxt);            % And calculate the
                                                     % voltage again
      end
   end

   Vsum_last = V;                                   % assign a final value

% Final calculations and the results to be stored in Panels
Volt(x) = V * numb;
Cur(x) = I;
Pwr(x) = I * V * numb;

End
```

# Appendix 3 PV Group

```
% For PV_Group
% Calculates the I-V and P-V characteristics for PV panels connected in series
%  as well as for a  "N" number of parallel branches.
% numb: is the number of PV panels connected in series.
% N: number of parallel branches.

function [Volt, Cur, Pwr] = pv_group(N, numb1, numb2, numb3, temp1, temp2, temp3, sun1,
sun2, sun3, Panel)

% setting the initial values
I = 0;
x = 0;
V = 0.001;

% Increasing current so voltage drops, until it becomes zero
while(V > 0)
   I = I + 0.001;
   x = x + 1;

% for faster numerical calculation
   if (x<=1)                                        % First Series Group
      nxt1 = 0;
   else
      nxt1=V1_last;
   end

   if (x<=1)                                        % Second Series Group
      nxt2 = 0;
   else
      nxt2=V2_last;
   end

   if (x<=1)                                        % Third Series Group
      nxt3 = 0;
   else
      nxt3=V3_last;
   end

 % Calling PV Model for each series group
V1 = pv_model2(I, sun1, temp1, Panel, nxt1);        % For Group 1
V2 = pv_model2(I, sun2, temp2, Panel, nxt2);        % For Group 2
```

```
V3 = pv_model2(I, sun3, temp3, Panel, nxt3);        % For Group 3
V = V1 + V2 + V3;                                   % Total Voltage of
                                                     % 3 series groups


% If voltage deviation is greater then reduce current to get a better
% voltage
    if (x>2)
      dev_V = Vsum_last - V;                        % Value difference
      if (dev_V>12)                                 % Now checking if the
                                                     % value difference is > 12?
          I = I - 0.0009975;                        % If so, then Reduce the
                                                     % current again




% And calculating the voltage again
 V1 = pv_model2(I, sun1, temp1, Panel, nxt1);       % For Group 1
V2 = pv_model2(I, sun2, temp2, Panel, nxt2);        % For Group 2
V3 = pv_model2(I, sun3, temp3, Panel, nxt3);        % For Group 3


 V = V1 + V2 + V3;                                  % Total Voltage of 3
                                                     % series groups again
      end
   end

% Assign final values for V = V1+ V2 + V3
V1_last = V1;
V2_last = V2;
V3_last = V3;


 Vsum_last = V;                                     % Assign final value

% Final calculations and the results that have to be stored in Array
Volt(x) = (numb1*V1)+(numb2*V2)+(numb3*V3);
Cur(x) = N * I;
Pwr(x) = N * I * Volt(x);

end
```