CHARACTERIZATION OF NON-NORMAL OPERATING CONDITIONS OF OUTDOOR PHOTOVOLTAIC (PV) POWER GENERATOR MODULES: GLOBAL AND A NEPAL CASE-STUDY

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ABSTRACT

The energy consumption is increasing day by day. We are marching towards the renewable energy sources for the healthy environment issues. Among the various renewable sources, the solar energy is one of the most abundant. PV cell is a technology that generates direct electrical power from semiconductors when they are subject to illumination. The PV cell technology has enhanced the usage of solar energy primarily due to the manufacturing cost reduction and improvement in the power conversion.

The purpose of this work is to study the operating characteristics of PV system in the case of the non-normal operation conditions. The installed PV system has to operate in abnormal environmental conditions which lead to adverse effects on the PV system performance, so there is the need of systematics study of those conditions. The systematic study includes the detail analysis of the variation in the output characteristics, i.e., current, voltage and power. The waveform of current and voltage of the PV cell, module and panel are measured and recorded. The waveforms are recorded for normal operating condition, as well as the abnormal conditions. The obtained curves are then compared and the problem is associated with the PV system is identified. An algorithm has been presented for detection of faults.

Nepal is a country with huge potential of solar energy. There is an increasing of the PV installation, but they lack the monitoring and management of the installed system, so it is required to study about it.

Keywords: Renewable energy, PV systems, Solar cells, PV faults, Operation and maintenance

RESUMO

Por questões ambientais, as fontes de energia renováveis ganham um peso cada vez maior no domínio da produção e consumo de energia. Entre as fontes de energia renováveis destaca-se a energia solar fotovoltaica (PV). Esta tem tido um grande incremento devido à diminuição dos custos envolvidos e ao aumento das eficiências dos processos de conversão energética envolvidos.

As análises de falhas do sistema PV é uma tarefa fundamental para garantir a confiança e eficiência do sistema. O objetivo deste trabalho é o estudo das características de funcionamento do sistema PV em condições anormais. Danos físicos, sombreamento, envelhecimento, estragos nos díodos de contorno, são alguns exemplos de condições referidas como anormais. É importante um controlo sistemático do sistema. Esse estudo inclui a análise pormenorizada da variação das características de saída (corrente, tensão e potência). Cada falha tem associado um dado sintoma, que permite a sua caracterização. É apresentado um algoritmo para a deteção de falhas. Várias simulações foram levadas a cabo para as diferentes falhas e as respetivas comparações com os resultados experimentais foram realizadas para validar os módulos PV.

É apresentado o caso de estudo do Nepal, país com um grande potencial fotovoltaico, embora ainda não totalmente aproveitado. Existe um aumento da instalação de sistemas PV, mas com uma monitorização e gestão do sistema já instalado incipientes. O presente trabalho tenta identificar as falhas frequentes e as causas de degradação, recomendando soluções para os problemas encontrados.

Acknowledgement

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TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

LIST OF ACRONYMS

AEPC	Alternative Energy Promotion Centre
Imp	Current at maximum power
INGO	International Non-Governmental Organisation
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
NGO	Non-Governmental Organisation
NOCT	Normal Operating Condition
PV	Photovoltaic
PVT	Photovoltaic thermal
STC	Standard Test Condition

LIST OF SYMBOLS

A	Ampere
AC	Alternating Current
Eg	Energy band eV
eV	Electron volt 1.602×10^{-19} joules
G	Irradiance (W/m2)
GW	Giga Watt
I_D	Diode current
I_L	Photo current
Imp	Current at maximum power
I_O	Inverse saturation current
Isc	Short circuit current
Isc_r	Short circuit current in reference condition
Ish	Parallel loss current
IV	Current-Voltage
k	Boltzmann constant 1.380×10^{-23} m^2 kg s^{-2} K^{-1}
K	Kelvin degree
mA	Milliampere
MW	Mega Watt
PV	Photovoltaic
q	Charge of electron modulus $1.16*10^{-19}$ Coulombs
R_p	Shunt Resistance
R_s	Series Resistance
T	Temperature in Kelvin
V	Voltage
Vmp	Voltage at maximum power
Voc	Open Circuit Voltage
V_T	Thermal Voltage 25.85 mV

1. INTRODUCTION

The generation of energy from the fossil fuels emit greenhouse gases, result in global warming which is unfavourable for the environment and ecosystem. These problems lead to the use of the environment-friendly renewable energy resources like wind, solar, geothermal, tidal, and so on. Among these renewable resources, PV solar energy is gaining its global popularity. Nevertheless, the advancement of technology the bottlenecks is still associated with high cost and low efficiency. In addition to the high capital cost, it's maintenance cost is high because they are installed outside so they are prone to various mechanical and electrical faults. These faults results increase in the power loss and decrease the efficiency as well as the reliability of the system. There is five level of faults that can occur in the PV system i.e. cell level, group of cell level, module level, string level and array level. Each level faults have its own characterizes so a proper model has to be made to identify the location of faults. Each level also has different types of faults so the modelling should be done promptly and should include all the probable modelling of the system.

The analysis of different faults is very useful to characterize the faults which are very for the recognition of faults for the whole system. The probable faults in the PV system are partial shading, open circuit, short circuit, hotspots, mismatch, aging. The simulation of these faults conditions eases the analysis behaviour of the faults. Modelling and design calculation of PV system requires the knowledge of the parameter which describes the non-linear characters of PV cell. These parameters are calculated with the Dark current-voltage measurement method. After determining these parameters, it is easy to characterize the system and easy to model of the system. Modelling must be done from each level and should measure the quantity for the future reference.

Nepal is a developing country struggling with the energy crisis. The government of Nepal is concerning about the meeting the demand of energy through the renewable resources. The solar PV system has been a good source of energy for the off-grid population of Nepal since all the population is not connected to the grid. Nowadays not only the remote areas, a solar PV system has gaining its popularity in the cities areas too and many business firms, normal people have installed this system to their business house, home etc, so there is need of study of the non-operating conditions and faults in Nepal. This thesis work focus study of the potentiality of the solar PV system and its status. The measure problem has been identified and its measurement and recommendation have been made.

1.1. Motivation

As the demand for clean energy is increasing due to the global warming and pollution issues, PV solar power generation has an important role in the clean energy. Now all the developed countries are focusing on this renewable source of energy. The capital cost and maintenance cost for PV power generation is very high. It is necessary to supervise and monitor the unfavorable operating condition to ensure they are working correctly. It is required to have high efficiency and long-life span of PV system. Since the PV panel must mount on the open place so it is always prone to various defects. This kind of unfavorable conditions can degrade the efficiency of the solar panel. The decrease in the efficiency of PV panel can cause heavy loss to the owner because the cost of the panel is very high as compared to other energy sources. To save the money and environment it is necessary to monitor and supervise the condition of the PV system. The one of the method to monitor faults on the system is the supervision of output current-voltage characteristics, the analysis of current-voltage curve for each unfavorable condition characterize its pattern, so this characteristics pattern is the very important tool in future for the monitoring and fault analysis of the system.

Nepal is a small developing country, focusing on the renewable solar energy to meet the energy demand. Nepal has a huge potential of solar PV energy due to its geographical advantage, and there is increasing demand for the solar PV system though there are only the off-grid system exits. Till now there is collectively not more than few megawatts has installed but now the government is focusing on the flourishing the PV power. In this condition, it is necessary to be updated with the various faults and non-operating conditions in Nepal. A systematic study of the faults and maintenance of PV system in Nepal has not been done yet, so it’s a great chance to have such opportunity of doing something that has not been done

1.2. Objectives

PV system must withstand the various environmental conditions. The output power of PV system is highly dependent on the operating conditions. The objective of this thesis is to study the current and voltage characteristics of the PV system for the different unfavourable conditions. The waveform of current and voltage changes with the operating conditions and plays vital role in determining the faults. These changes presented by waveforms are studied and identify the characteristics of faults. This characteristic is then used to determine the fault associated with the system.

Finally, this thesis work finally improves the reliability of the PV system. This thesis work also focuses on the condition of PV system in Nepal and try to identify the problems associated with the PV system and their remedies. This thesis work can be a reference to the people who are interested in PV system in Nepal.

1.3. State of art

The demand for clean energy is increasing day by day as the global warming and climate change have been a serious problem for the world. Most of the countries are developing the technology to harness the renewable energy that is environmentally friendly. They utmost try to avoid the use of Fossil fuel. Thinking about the renewable energy resources, there are different types of renewable resources like wind energy, solar energy, geothermal energy tidal energy etc. Among these different kinds of renewable energy solar energy is the major energy source. Solar energy can be harnessed in different ways choosing the appropriate technology. Among them, the most common are solar PV (PV), solar thermal and hybrid solar PV/thermal (PVT) [1]. Electricity is the most versatile form of energy. It can be transformed into various forms of energy as it is required it to be. The PV effect is a technology that transforms a solar energy into electricity (dc) with the help of semiconductor device. In the last decade, solar power generation from PV cells has had a large increase. The fig 1-1 shows the basic level of the solar cell to the PV system, its formation along the various levels.

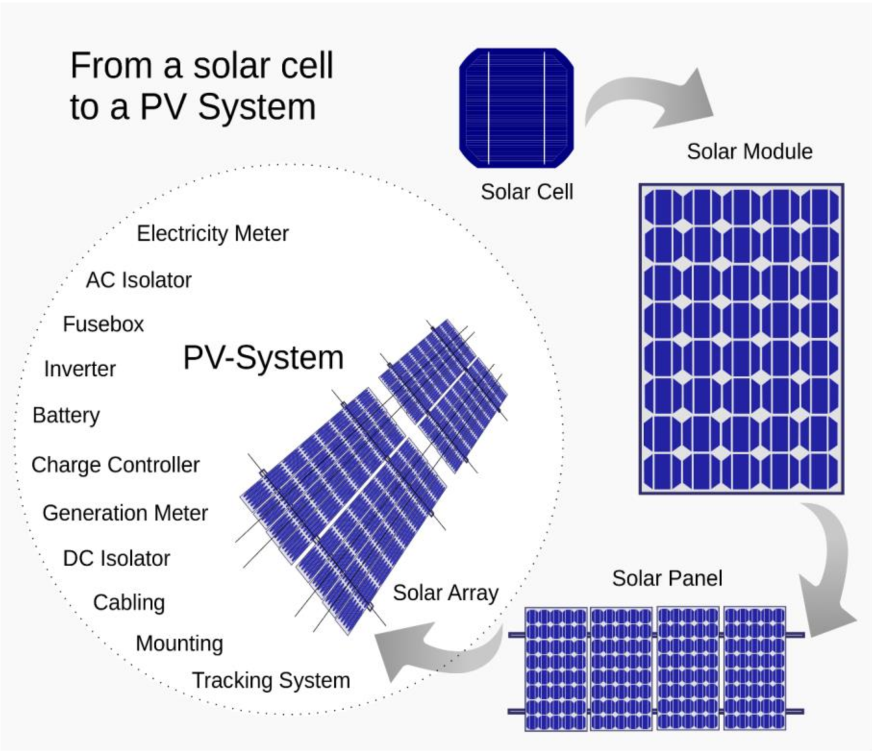


Fig. 1- 1 A PV system [2]

A recent development involves the makeup of solar cells to increase its efficiency. The most efficient type of solar cell to date is a multi-junction concentrator solar cell with an efficiency of 46% [3]. The highest efficiencies achieved without concertation include a material by “Sharp corporation” at 35.8 % [3] using a proprietary triple-junction manufacture technology. There is an ongoing effort to increase the conversion efficiency of PV cells and modules. Recent developments in Organic PV cells have made significant advancement in power conversion efficiency. The other recent development includes the discoveries of Light-Sensitive Nanoparticles, Gallium Arsenide new material that could make three times more efficient than existing products on the market [3]. There has been a study to the solar panel with built-in battery and other manufacturing material.

1.4. Development of PV Technology

The history of PV begins with the nineteenth century, the first fictional, intentionally made PV device was by Fritts [3]. The modern era of PVs started in 1954 when researchers at Bell Labs in the USA accidentally discovered that p-n junction diodes generated a voltage when the room lights on [3]. Then there has been a start of the study of the PV system and its development, In the 1980s the industries began to give emphasis on the manufacture of PV cells [3]. Initially, the cost of manufacture of PV cells are expensive but along with the time the cost has been decreasing and the efficiency has increased.

Solar PV technology has evolved a lot since it has been discovered. Solar PVs are taken as a thing of today and future. The development of material technology, monocrystalline silicon and multi-crystalline silicon are now economically viable to produce in large quantity [4]. However, their energy conversion efficiency from solar to electricity is still low Researchers have long looked-for ways to improve the efficiency and cost-effectiveness of solar-cells. The average solar cell is approximately 15 % efficient which means nearly 85% [5] of the sunlight is not converted into electricity.

Solar PV is growing rapidly and worldwide installed capacity reached at least 177 gigawatts (GW) by the end of 2014 [3]. The total power output of the world's PV capacity in a calendar year is now beyond 200TWh of electricity [3]. The fig. 1-2 shows the global scenario from the past decade to come 2020. It shows the trend with an estimated installation of around 600 GW by the end of 2020. More than 100 countries use solar PV China, followed by Japan and the US is now the fast-growing market while Germany remains the world largest producer [3] can be seen in fig. 1-3.

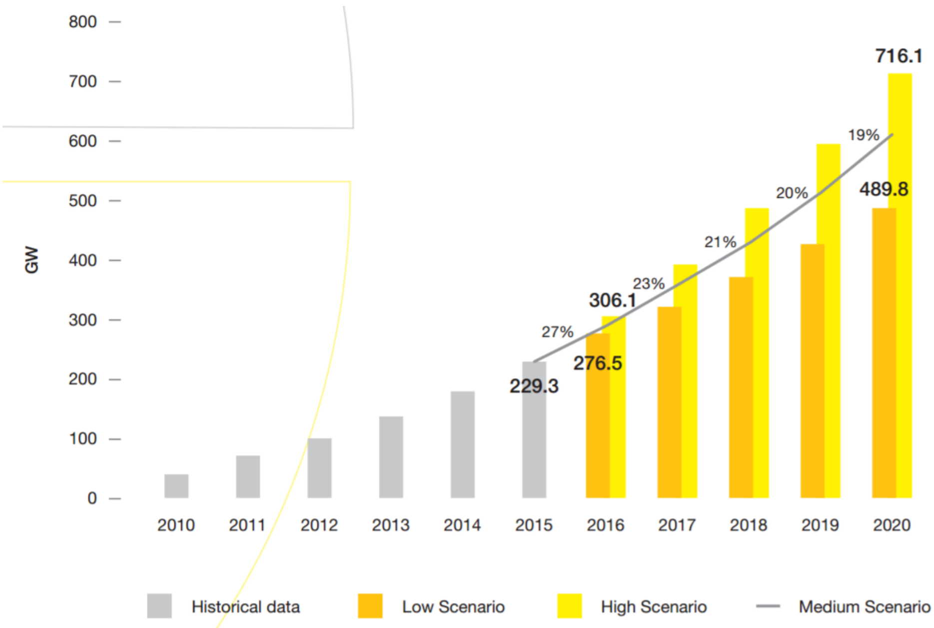


Fig. 1- 2 Global solar PV market scenario [6]

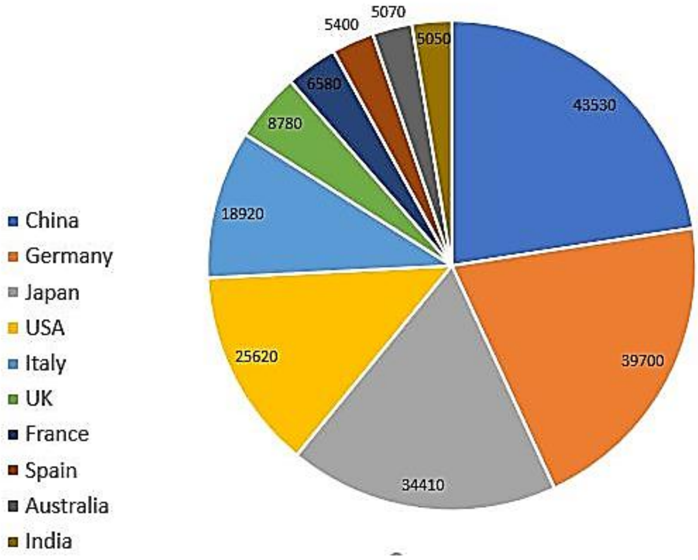


Fig. 1- 3. Top 10 countries in 2015 based on total PV installed capacity (MW) [7]

2. SOLAR CELL MODEL

The solar cell is a basic unit block of a solar PV system which is made of two layers of semiconductor materials. When the photon with sufficient energy strikes the surface of the solar cell, electron and hole pairs are released which causes to a generation of electricity. A solar cell works on the principle of PV effect. Basically, the silicon is doped with pentavalent and trivalent impurities to increase the charge carrier concentration and these oppositely doped layers are brought together to form a junction. In the junction after the photons are absorbed the free electron of n region try to move to p-region and holes of p-region try to move to the n-region to compensate for their respective deficiencies. If electrical contacts are made with the two semiconductor materials, the free electrons will flow from the n-type through the external path to the p-type material. The flow of electrons through the external circuit will continue as long as more free electrons and holes are formed by the solar radiation[3].

There are various electrical circuit models of PV cells which have been widely described in the literature [8] [9] . A most commonly used model is the one-diode model (Ideal model) as shown in the fig. 2-1. In one diode model, a cell is represented by a current source I_L in parallel with a diode and a resistance (Rsh) with and a series resistance (Rs).

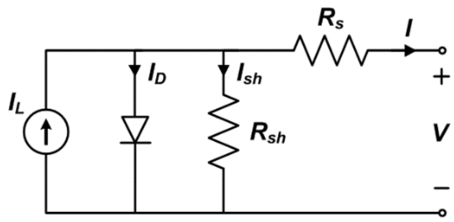


Fig. 2- 1. A single diode model of a solar cell. [10]

The governing equations for this model is given as:

$$I_{sh} = \frac{V+IRs}{Rsh} \tag{2-1}$$

$$I = I_L - I_D - I_{sh} \tag{2-2}$$

$$I = I_L - I_0\{e^{(\frac{V+IRs}{Vt})}\} - \frac{V+IRs}{Rsh} \tag{2-3}$$

2.1. Current-Voltage Curve of a Solar Cell and Module

The current-voltage curve of a PV panel describes its energy conversion capability at the existing conditions of irradiance and temperature. The IV curve provides a quick and effective means of accessing the true performance of solar cell. As shown in the fig. 2-2, the curve represents the combinations of current and voltage at which the string could be operated or ‘loaded’, if the irradiance and cell temperature could be held constant. The current-voltage curve of a PV panel is non-linear graph. The curve is highly dependent on the irradiance as well as the temperature of the cell and with the local weather condition too. Since the different solar panel has a different parameter so it will result in the different IV curves. The behaviour of the current of a solar cell is nonlinear described by above equations (2-3). The typical IV and PV curve of a solar cell is shown in fig 2-2.

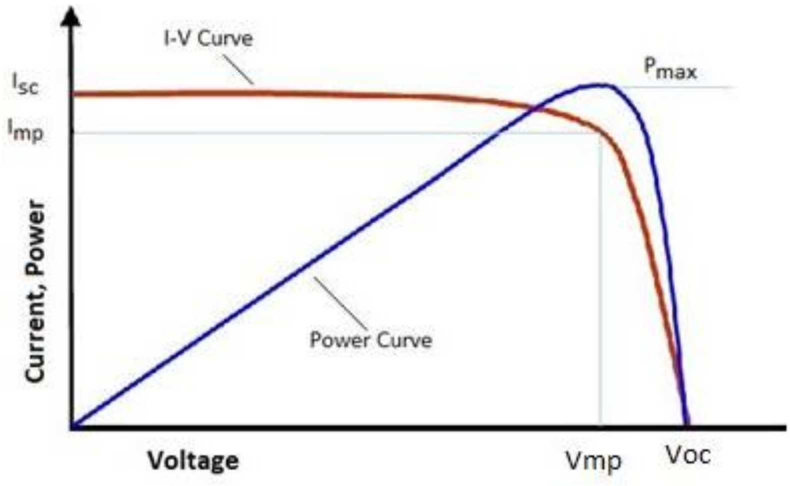


Fig. 2- 2 IV and PV curves of a solar cell [11]

The important parameters of IV and PV curve are the following

- Short circuit current (Isc): Maximum value of current generated by a solar cell when the voltage is zero;
- Open circuit voltage (Voc): Maximum value of voltage generated across cell when there is open circuit of cell;
- Maximum power point: The maximum value of power that can be extracted from a cell/module;
- Imp: The value of current of a cell at MPP.
- Vmp: the value of voltage of a cell at MPP.
- Fill factor (FF): It's a ratio of the maximum power from the solar cell to the product of Voc and Isc.

$$FF = \frac{Imp*Vmp}{Isc*Vsc} \tag{2-4}$$

The IV curve of a PV module is shown in the fig 2-3. The IV curve changes with irradiance [3] and operating temperature of a panel. The study of the current-voltage characteristics of the PV panel is done with comparing the standard current-voltage curve versus the measured curve of the panel. Occasionally the measured IV curve deviates substantially with the standard IV curves [11]. The changes in the curve are the results of various reasons, probable damages, or defects and aging etc. The deviation in the curve can provide the information of the performance of the panel. The study of the IV characteristics curve provides the following deviations in the PV panel according to the various defects and aging.

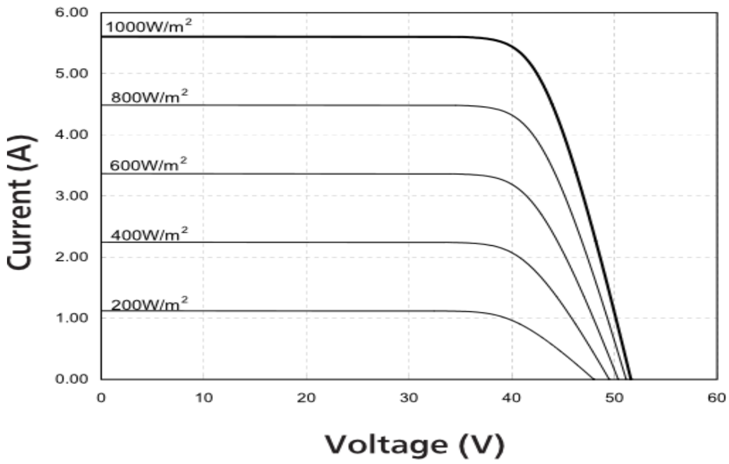


Fig. 2- 3 Current voltage characteristics [12]

2.2. Determining I-V and P-V characteristics of solar cells

Theoretically, the IV characteristic of a solar cell is determined by changing the voltage applied to the cell in progressive steps from zero to infinite resistance. In practice, to obtain this curve are used 6 distinct methods. These methods consist in using a variable resistor, capacitive load, electronic load, bipolar power amplifier, four-quadrant power supply or a DC to DC converter as shown in table 2-1. A comparison between these 6 methods can be seen in figure. In this thesis, a variable resistor is used, so it was not much convenient to obtain all the data from the experiment.

Table 2-1 – Different methods for determining the IV curve of a PV module

Types	Flexibility	Modularity	Fidelity	Fast Response	Direct display	Cost
Variable resistor	Medium	Medium	Medium	Low	No	low
Capacitive load	Low	Low	Medium	Low	No	High
Electronic load	High	High	Medium	Medium	Yes	High
Bipolar Power Amplifier	High	High	high	Medium	Yes	High
4-quadrant power Supply	Low	Low	high	High	Yes	High
Dc-Dc converter	High	High	High	High	Yes	Low

2.3. Solar cell materials

Silicon is the most used semiconductor for the manufacture of the solar cell. Pure silicon is crystalline in structure which is necessary for solar cells. Silicon can be arranged into either a monocrystalline structure or a polycrystalline structure. Polycrystalline shells are made by using various silicon crystal together and are less expensive in cost than monocrystalline. Once the silicon has been properly prepared, it is doped with phosphorous (donor dopant) and boron (acceptor dopant) to for a semiconductor. The electrical properties of silicon depend on the amount of the dopant materials. There are other semiconductor materials, choice of the material depends upon the energy gap, efficiency, and the cost.

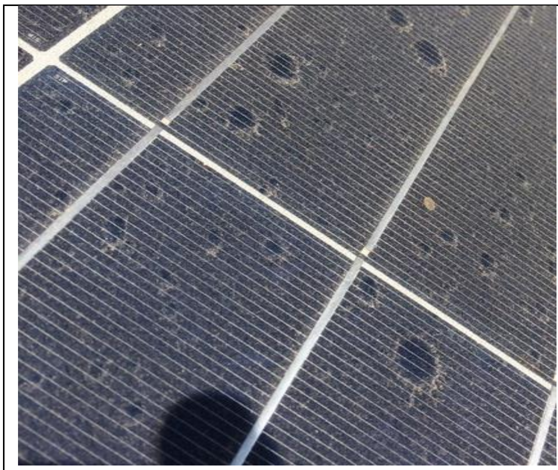
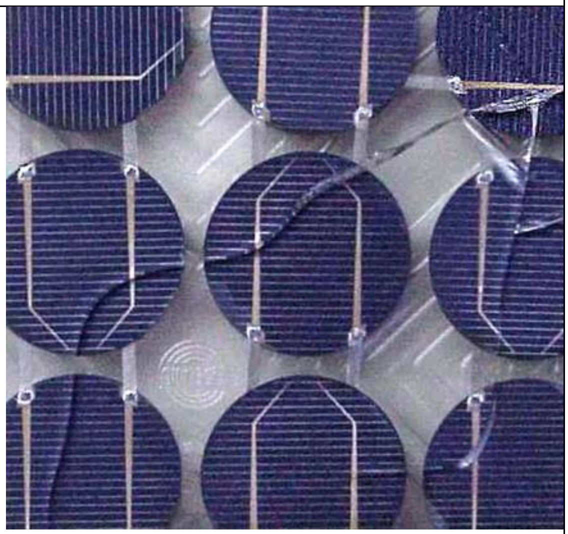
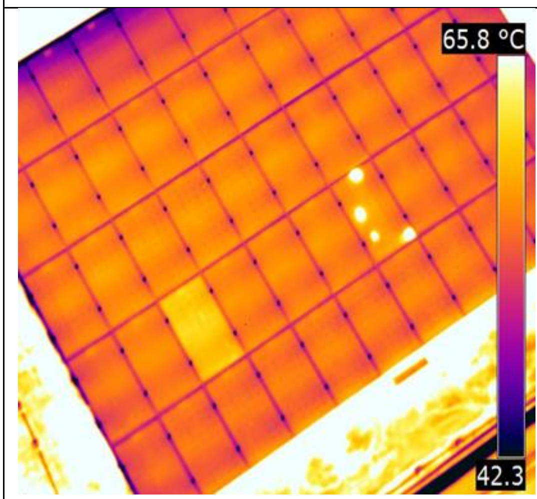
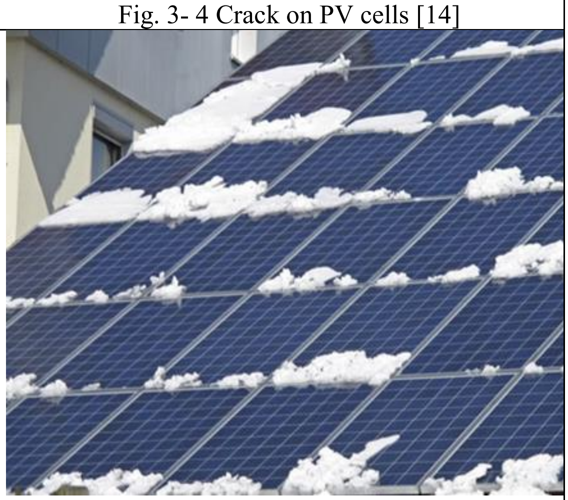
3. ABNORMAL CONDITION IN PHOTO-VOLTAIC SYSTEMS

Since the PV panels are operated in outdoor conditions, they are exposed to various environmental and sometimes harsh conditions as, dirt and dust, partial shading, rain, snow, corrosion which can lead to a faster aging [4]. A very basic approach to detect an abnormal condition is to compare the output power of the panel with the reference power and get notified when there is a difference more than some tolerance. The approach that we are going to adopt in this thesis work will be to analyze the IV curves (one or for an array of panels) for the most common abnormal conditions [11]. The study of the IV curves includes the analysis and measurement of characteristics of the current, voltage and power for the most frequent abnormal conditions. The measured curves are then compared with the characteristic ones of the healthy panel (or healthy arrays) or their initial condition to ensure the system has no significant abnormalities.

3.1. Faults in PV Systems

There are four levels of the components to form a PV system: the PV cell unit, cell groups, the PV module and a PV string. These components are always exposed to some defects that can affect the performance of the whole system[13]. The main task for this thesis is to figure out the probable faults for each of the components and its influence in the IV curve of the system. Table 3-1 lists the most probable defects as well as the non-normal operating conditions associated with the PV system in the real world.

Table 3-1 – Non-normal operating conditions of PV system

 Fig. 3- 1 Dust [14]	 Fig. 3- 2 Burnt cells [15]
 Fig. 3- 3 Damage PV modules[16]	 Fig. 3- 4 Crack on PV cells [14]
 Fig. 3- 5 Hotspots [17]	 Fig. 3- 6 Snow on PV modules [18]

3.2. Faults in a cell

As the solar cell is the basic building block of a PV system, it is susceptible to various faults and other non-normal operating conditions. Any defects in a cell can cause a severe effect on the performance of the whole system. The most probable defects in PV cell were listed in Table 3-2. To identify some abnormal condition in a cell, it is required to first obtain the IV characteristic curve of a "good" cell. After, it must be compared with the IV curve of a "faulted" cell. From an analysis of both IV curves, the fault can be detected and possibly classified.

The impact of a fault in a cell to a whole PV system must also be analysed. The most common fault in a cell, shading of a cell, is a mismatch. This is caused by combining the cells in the group having non-identical IV curves. The variation in some cell parameter can cause the mismatch of IV curves. The changes in these parameters are caused due to different physical properties of the cells and due to the different operating conditions caused by different defects, including the above-mentioned defects [19]. When the cells are group together forming a PV module and connected in series. The voltage produced by each cell is no longer equal to the same current. On contrary, when the cells are connected in parallel, the current produced by each cell is not identical to the same voltage. For this reason, it is necessary to determine each solar cell characteristic [19].

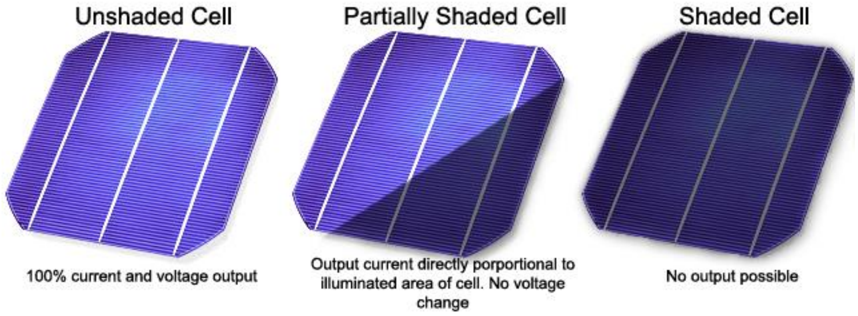


Fig. 3- 7 Shading on cells [20]

Table 3-2 – Variation of IV curve of a solar cell in different conditions

Area	Causes	Example of the curve
1	-Normal IV characteristic curve	Fig 3-7a)
2	- Increased series resistance	Fig. 3-7b)
3	– Shunt paths exist in the module – Shunt paths exist in the cell interconnections	Fig. 3-7c)
4	– Cracked or partial shading	Fig. 3-7d)
5	– PV cells are damaged – Bypass diode has short-circuited – Partial shading	Fig. 3-7e)
6	– Interrupted chain of cells or completely shaded cell	Fig. 3-7f)

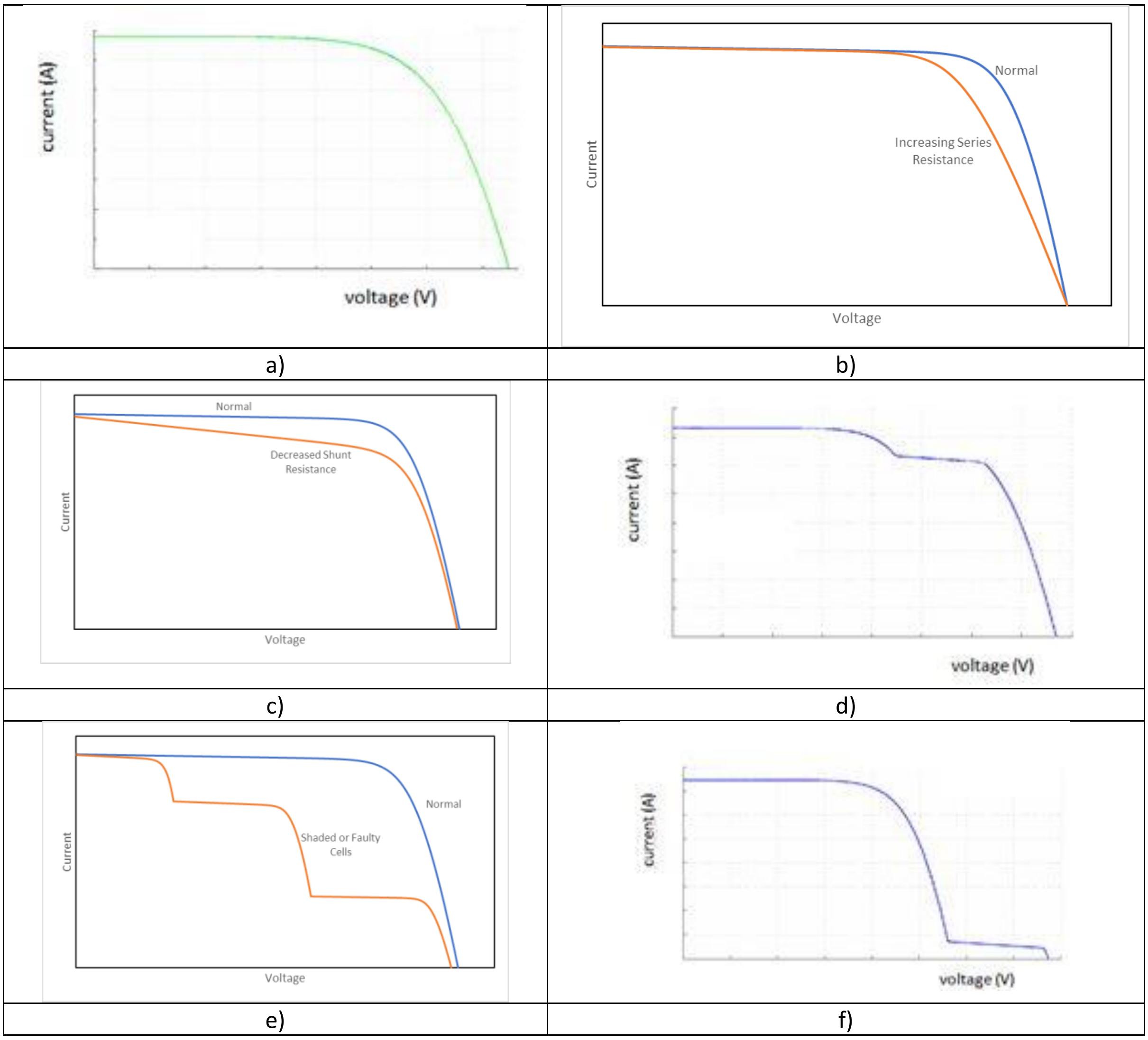


Fig. 3- 8 Solar cell in different operation conditions.

Partial shading is one of the most frequent situations that can induce abnormal conditions, occurring when some module of the PV array is shaded. This is a regular phenomenon mainly caused by clouds and/or nearby obstacles. Due to the nature of shading, it will show its influence on the IV characteristics [5]. The study of the nature of defects and its influences in the IV curves (either in a single solar cell and in a module), has found that module was broken, degradation, cracking, sand and snow effects, corrosion, and shading, all have in common will result in the variation of its fill factor. There can be also heating of the cells due to some defects, hotspots may occur due to the rise in cell's temperature [9]. There may be degradation of the interconnection between the modules, corrosion in the inter-cell bonds, all this will give rise to the variation of series resistance.

3.3. Fault on bypass diodes on a group of cells

A bypass diode is wired parallel with an individual group of cells as shown in Fig. 3-9 and 3-10, to provide a current path in case the cell (or module) becomes faulty or open circuited. The use of bypass diodes allows a series of the connected cells to continue supplying power at a reduced voltage rather than no power at all. The bypass diode is connected in reverse bias condition between the group of cells. Ideally, there would be one bypass diode for each cell but it is too much expensive, so there is a diode for each group of cells.

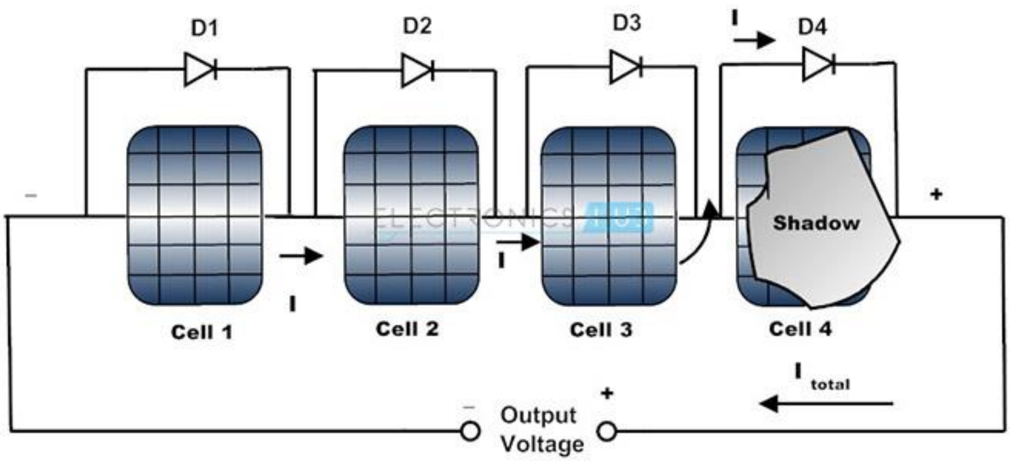


Fig. 3- 9 Shading on a cell [12]

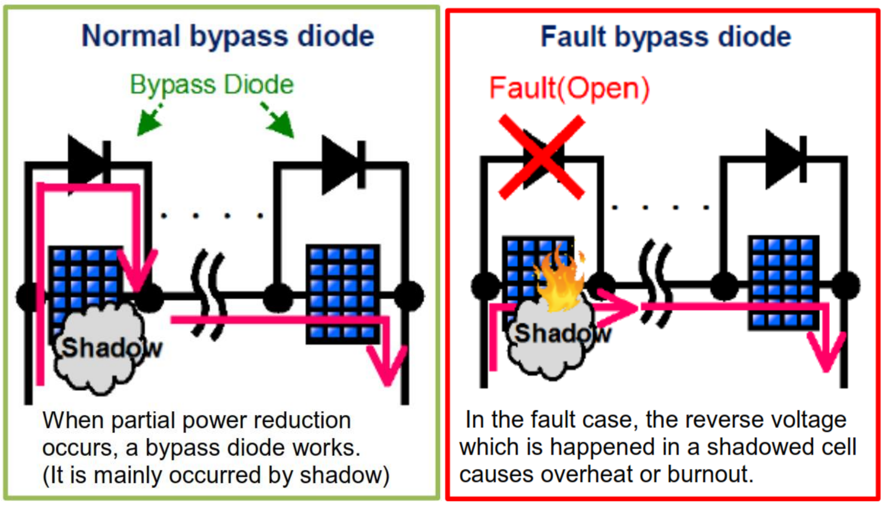


Fig. 3- 10 Fault on bypass diode[12]

The electrical faults associated with a bypass diode can be short-circuited diode, disconnected diode, and inverted diode, sometimes it may act as high impedance rather than a diode. In case of short circuit, the voltage of the group of cells becomes zero. The current of the group of cells in parallel is equal to the sum of the current flowing in the cells and it will circulate the short circuit path. In case of cells in series, the magnitude of the current flowing in the cells will be equal to the maximum current produced by one of the cells. Sometimes a bypass diode can act as an impedance [19], which causes the flow of current through it causing some power losses in that diode [8]. In case of an open circuit, there is no path for the current if there is a fault in a cell. In the case of reverse polarity, the diode starts to conduct when the sum of the voltage is greater than the voltage required to turn on the diode

Different studies [19] have been done on defects of the bypass diode. They show that there are some significant changes in the characteristic curve of the module. For the short circuit case, the overall voltage of the module decreases and so the power. In a case where a bypass diode acts as an impedance [19], the overall power decreases as the value of resistance increases and vice-versa. In the open-circuit case, the characteristics curve has drastic changes as in this condition another type of fault like shading plays a vital role in the modification of the curve. In case of reverse polarity, case the output power decreases as the reversal of polarity of the diode in the group can bypass the power when there is a greater voltage across the diode.

3.4. Faults in a PV Module

The PV module is prone to different faults. Since the module is the combination of series and parallel connection of numbers of cells with help of bypass diode. The electrical faults associated with the failure of a module of a PV system are short-circuiting of a bypass diode, reversal in the polarity of the bypass diode. The short-circuit of a diode causes the output voltage decrease. One reversal direction of a bypass diode also decreases the output voltage of group of cells. These faults can make significant changes in the IV characteristics of the system. The simulation of these faults is simulated in following simulation part.

3.5. Faults on a String

The PV array is the combination of series and parallel connection of the number of PV modules. The fault in a string is the fault associated with the PV module and non-return diode. The non-return diode may be short circuited or reverse biased. The short circuit of non-return diode may sometimes lead to the reverse flow of the current during non-normal condition. The reverse bias diode can oppose the flow of the current and lead to significant power losses. Sometimes the diode can act as the resistance this also lead to power loss. Apart from the fault in the bypass diode there may be opposite polarity connection of a PV panel within the string. there may chance of short circuit of the PV panel.

Mismatches are also likely to occur in the string. Mismatch in modules occur when the parameter of one modules is significantly changed from others. They are also likely to occur due to different environmental conditions [21] (i.e irradiance or temperature). Mismatch losses may lead to a serious problem causing drastic change in power generation.

The PV array can have some mismatch losses, these losses are caused because of change in electrical parameter in one module than others [11]. The difference environmental condition of module in a same string give such mismatch cases. The environmental conditions are irradiance, operating temperature

[18]. A manufacture faults may also lead to mismatch losses. Mismatch losses may cause serious problem. There are two kind of mismatch faults [11]:

3.5.1. Temporary mismatch:

Partial shading/ non- uniform temperature of PV system results the temporary mismatch in string. The shading caused by the position of the cloud is very common in large centralized PV system [22]. The consequences of this temporary fault have been already discussed in above sections.

3.5.2. Permanent mismatch:

Open circuit faults, aging, degradation, hot spots caused by the defects on the bypass diode, these are the general causes of the permanent mismatch [23]..

3.6. Aging

The solar panels are always exposed to open environment so they must bear harsh environmental conditions snow, dust, wind, temperature variations etc. The dust, soil, shading, water corrosion for long period can lead to aging of PV module [23][24]. Due to these environmental conditions, there is degradation of the performance of the PV systems. This degradation can be termed as the aging of a PV panel. The degradation may due to anti-reflective coating delamination, microcracks, encapsulation faults discolouring, delamination, and hot spots. There is no proper knowledge how the aging can be studied for PV cells but it has found that it can reduce the efficiency 13-25 % [13] of the solar panel in the duration of 15 years, the fill factor is reduced by 6-10 % [13] as shown in fig 3-11. In this thesis work, there will be an attempt to simulate the change in characteristics due to aging.

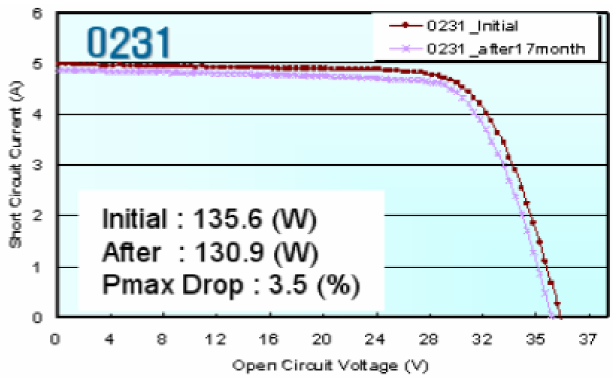


Fig. 3- 11 Degradation of performance due to aging of a solar panel [13]

4. EXPERIMENTAL TESTS TO DETERMINE THE CELL PARAMETER

4.1. The IV characteristics of cell in dark condition

All the solar cells have some parasitic resistances. To determine these parasitic shunt and series resistances an experiment is carried out known as dark current-voltage experiments [25]. Since it is done in the dark condition, so it is termed as a dark current-voltage experiment. The dark current-voltage experiment is commonly used to analyse the electrical characteristics of solar cells. It provides an effective way to determine parasitic parameters without the need of a solar simulator. The dark IV measurement technique provides such a diagnostic tool for module manufacturers.

4.2. Methodology

For the experiment the cell was covered with some objects so that it cannot receive any illumination and measurements were taken.

To determine the IV characteristic of a solar cell, it required a power supply, two Multimeters (one ammeter and one voltmeter) and one solar cell. The voltmeter was placed in parallel with the cell so that the voltage can be measured across its terminals and the ammeter in series. The electronic layout and assembly can be seen in the following fig 4-1 and fig. 4-2.

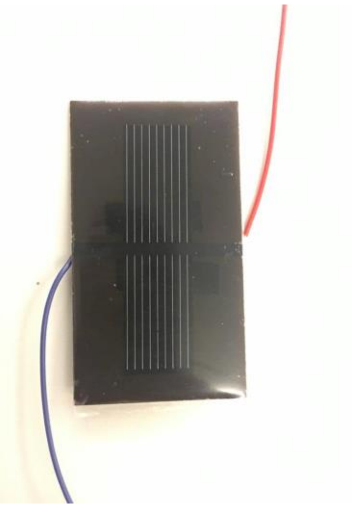


Fig. 4- 2 A Solar Cell

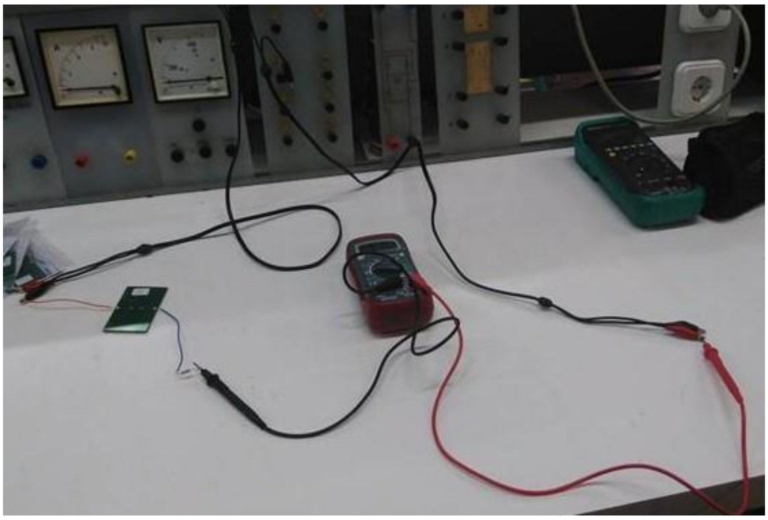


Fig. 4- 1 Experimental setup for measurement

With the aid of the power supply, the voltage was increased to the terminals of the solar cell, for each value, the current in the cell was measured. With this process, several points of Voltage-Current values were obtained that constituted the IV characteristic of that cell as shown in fig 4-3.

4.3. Current-Voltage characteristics of an experimental cell

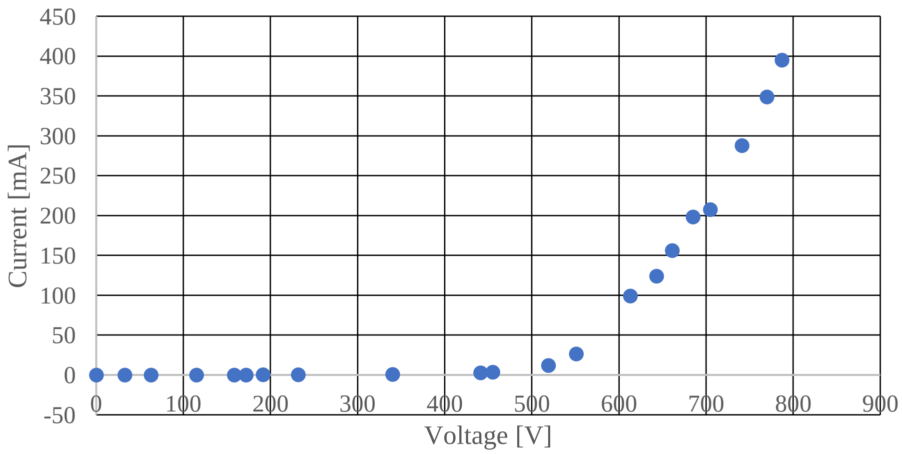


Fig. 4- 3 Experimental IV characteristics of a solar cell

The IV characteristic showed the behaviour of solar cell is like a diode. Since the experiment is performed in darkness, it is normal for the characteristic to resemble that of a diode. This characteristic makes it impossible to determine the values of V_{OC} and I_{SC} of the solar cell however, it is used to calculate the other solar cell parameters.

The data provided by manufacture company are following: Imp = 400mA; Vmp = 0.5V; Voc = 0,59V; I_{SC}= 433mA.

4.4. Determination of parameters for computational analysis

There are various solar cell models [26] [27]. For convenient, one diode three parameters model is chosen as shown in fig 4-4. The equivalent model of a solar cell is as follows:

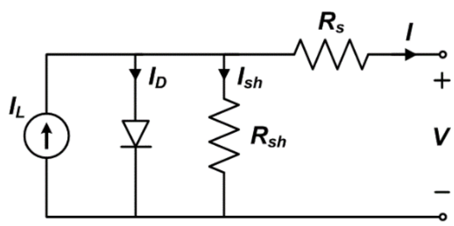


Fig. 4- 4 The equivalent circuit of a cell 1 diode model [10]

$$I = IL - Io \langle \exp\left(\frac{V+IRsh}{N*Vt}\right) - 1\rangle - \left(\frac{V+IRs}{Rp}\right) \quad (4\text{-}1)$$

Based on the dark IV curve, the parameters to be determined are:

- Ideality factor, m;
- Inverse saturation current, $I_{0;}$

- Series resistance, $R_{S;}$
- Shunt resistance, R_{sh}.

4.4.1. Ideal factor (m)

The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation. The ideal factor of a solar cell is calculated from the following formula (4-2) and obtained the value of 1.333.

$$m = \frac{Vmp_r - Imp\_r}{Vt_r * \ln(1 - \frac{Imp_r}{Isc_r})} \tag{4-2}$$

4.4.2. Inverse Saturation current at STC (Io)

The inverse saturation current of a solar cell is calculated using the following formula and obtained the value $2.9104e^{-8}$ A.

$$Io = \frac{Icc_r}{e^{\frac{Voc_r}{m*Vt_r}} - 1} \tag{4-3}$$

4.4.3. Shunt Resistance (Rsh)

The method [28] used to determine parallel resistance is based on the linear region of the IV characteristic of the cell with inverted current and voltage axes, as is shown the following figure.

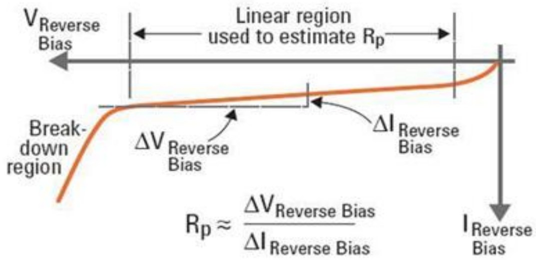


Fig. 4- 5 Measurement of Shunt resistance [17]

The linear region of the cell under study is shown below in fig 4-6.

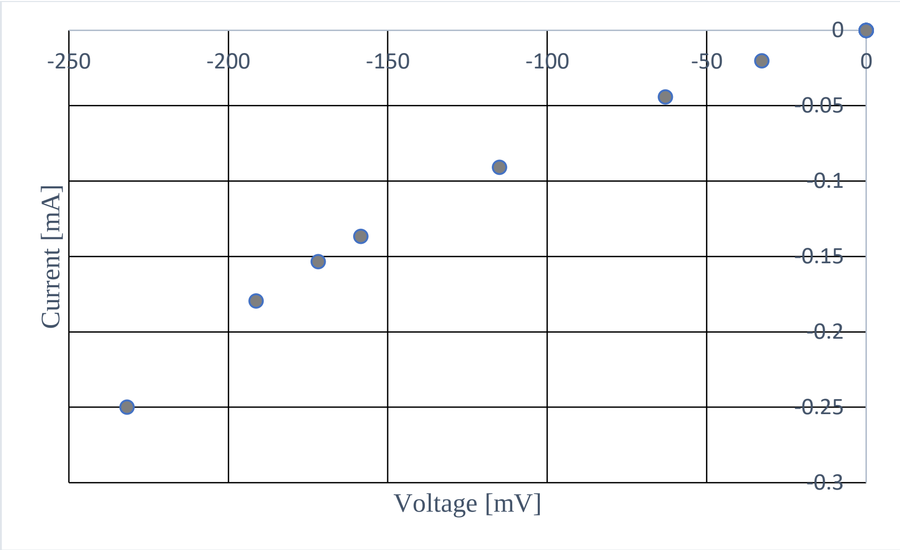


Fig. 4- 6 Voltage and inverted currents in linear region.

The shunt resistance can then be calculated as:

$$R_{sh} \approx \frac{\Delta V_{Reverse\ Bias}}{\Delta I_{Reverse\ Bias}} \tag{4-4}$$

$$= \frac{-0{,}1913 - (-0{,}0327)}{[-0{,}1795 - (-0{,}0202)] * 10^{-3}} = \frac{-0{,}1586}{-0{,}1593 * 10^{-3}} = 995{,}6\ \Omega$$

The value for shunt resistance of the modules tested is normal for commercial cells.

4.4.4. Series resistance (Rs)

The method in [29] was used to determine series resistance is to consider the model of two exponentials, where one of them refers to Rsh and another to Rs. The exponential for Rs is used for higher voltage values. It is then understood that:

$$I = I_{s1}.\left(e^{\frac{q(V-I \cdot R_S)}{n1 \cdot K \cdot T}} - 1\right) \tag{4-5}$$

For I much larger than I_{s1} so equation……. vi becomes

$$I = I_{s1}.\left(e^{\frac{q(V-I \cdot R_S)}{n1 \cdot K \cdot T}}\right) \tag{4-6}$$

And following equivalences:

$$lnI = lnI_{s1} + \alpha_1(V - IR_s) \tag{4-7}$$

Taking a point from the IV curve (V0, I0) comes:

$$InI - In0 = \alpha 1(V - IRs) - \alpha 1(V0 - I0Rs) \quad (4\text{-}8)$$

Being X = $\frac{V-V_0}{I-I_0}$ and Y = $\frac{\ln(\frac{I}{I0})}{I-I0}$, this gives a straight line:$Y = \alpha 1(-Rs + X)$

Next, the values of the IV curve of cell 10 were used, with voltages and currents starting at V = 0.34 V. X and Y were calculated, giving 24 pairs of values. Subsequently, with a fitting the line was obtained: Y = 13.82 * (1.104 + X). That is Rs = 1.104 Ω

The values that obtained are for the parasitic elements of a diode are higher than the real values. The calculated value for shunt resistance is 995.6 Ω which is as normal value for commercial cells. The series resistance is 1.04 which is too high, it should be less than 0.1 Ω for commercial purpose. The reason for the high value of series resistance may be the calculating method is not accurate as it converts the non-linear curve to linear form, this results in a chance of some error. It is required to adopt another way of to determine this parameter described in section 4.6

4.5. Limitation and conclusion of Dark Condition

A problem consists of the measurements of the IV curve in the darkness: the current flows in the opposite direction and the current paths are different. The change in the path of the current causes a lower series resistance in the measurements in the darkness in relation to the measurements with light.

The equation of the equivalent scheme of a solar cell makes it impossible to perform a fitting with exactness, even knowing the pairs of voltage and current values. Approximate methods could be used if one knew the V_{OC} voltage and the I_{SC} current, but for the characteristic, both values are unknown and do not apply. As such, the only parameter that was calculated was the parallel resistance, through an approximate method, which resulted in 995.6Ω.

But there is a research work that says that it is possible to calculate the values V_{OC}, Imp and V_{MP} very close to the real ones, knowing only the parameters calculated by dark IV: "Using the cell parameters determined from dark IV analysis, it is possible to calculate a module's expected Light IV performance by prescribing a value for Isc and inserting the parameters in a two-diode electrical model [30].

In general case, the average I_{SC} of cells is typically a well-known quantity since manufacture company provides it. Work by others has shown that for individual cells, the Rs parameter determined from dark IV measurements differs, and is usually lower than the value determined from light IV measurements [25]. This work has demonstrated the same difference for dark IV measurements on modules. The cause for the difference in calculated Rs is that the imposed voltage distributions and consequently the current flow patterns are different in dark IV versus light IV measurements.

Nonetheless, dark IV measurements provide a valuable method for analysing module performance parameters

4.6. Calculation of cell parameters using a fitting function

Using a numerical software, a fitting of the IV curve was done with a non-linear regression. This function, eq. (4-9) was used to fit the curve and help to determine the cell parameters. The equation 4-1 represents a behaviour of non-linear equation where the data from the table 4-1 is provided.

$$f(x) = I - I_{PV} + I_S.\left(e^{\frac{q(V+I\cdot R_S)}{n\cdot K\cdot T}} - 1\right) + \frac{V + I\cdot R_S}{R_{sh}} * \left[1 + k\left(1 - \frac{V+R_S I}{V_b}\right)^{-n}\right] \quad (4.9)$$

Table 4-1 – Experimental IV curve obtained.

Voltage [V]	Current [mA]
0.439	2.26
0.4980	5.94
0.523	10.61
0.546	19.43
0.553	23.65
0561	29.47
0.569	36.84
0.577	46.6
0.584	55.9
0.587	61.6
0.59	66.8
0.594	75.2
0.599	85.2
0.603	95

The obtained results from the theoretical calculation in section 4.4 and from this fitting method are quite different, this is the fact that the fitting was done using the non-linear IV curve and the theoretical calculation was done with the linearization of the equation.

Using the initial points x_0 = [Iph0 I00 Rs0 Rsh0 Vt0] = [0 10^{-8} 0.015 5 0.0308], the parameters for which the function converges are: x = [0.0034 -4.2357e-10 0.0504 31.4961 0.0306].

Table 4-2 – *Simulation Results*

Iph	I0	Rs	Rsh	Vt
0.0034	4.2357e-10	0.0504	31.4961	0.0306

4.7. Comparison of the obtained results

The previous obtained parameters were used in the P-Spice, a software program, and plotted an I-V curve of a diode. The equivalent circuit model for simulation in P-Spice is shown in figure 4-7. The obtained IV curve is shown in figure 4-8. The table 4-3 shows the data from dark current experimental work and from P-spice simulation. This table shows that the obtained parameters are quite near the exact value. The data obtained for high voltage values are relevant. The relative error has decreased as the supplied voltage has increased. The high relative error for low voltage may be results of unable to take the precise reading because the data are in the milliamperes and small changes can make huge difference in the calculation.

With these results one can use the obtained parameters to characterize the PV cells used in this work.

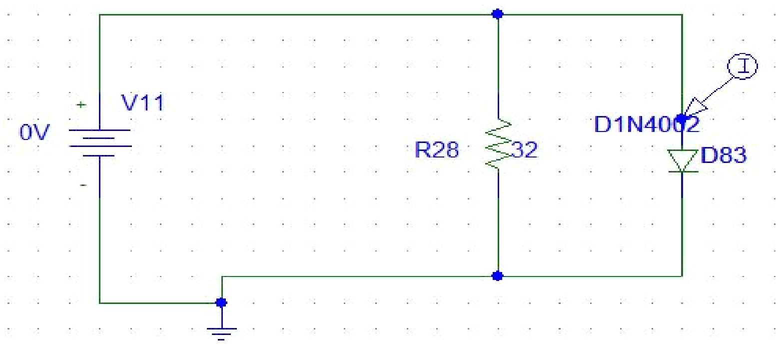


Fig. 4- 7 Equivalent circuit in P-spice

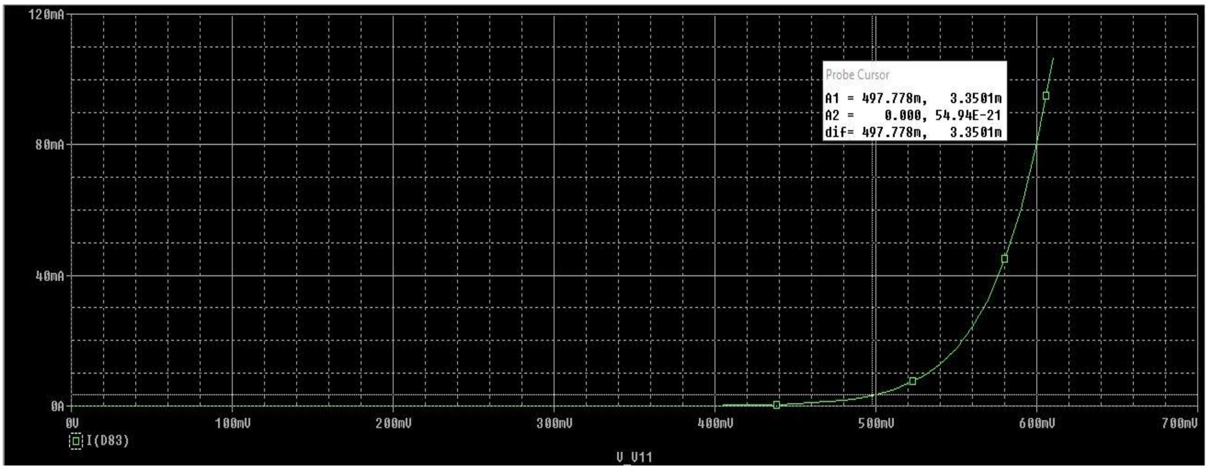


Fig. 4- 8 characteristics obtained from Pspice

Table 4-3 – Comparison of values

Voltage[V]	Current Experimental[mA]	Current Pspice[mA]	Relative Error(%)
0.439	2.26	0.5	77.87
0.498	5.94	3.45	41.91
0.523	10.61	7.56	28.78
0.546	19.43	16	17.65
0.553	23.65	19.7	16.70
0.561	29.47	25	15.16
0.569	36.84	32	13.13
0.577	46.4	41.8	9.91
0.584	55.9	50.1	10.37
0.587	61.6	55.3	10.22
0.59	66.8	59.9	10.32
0.594	75.2	68.56	8.82
0.599	85.3	78	8.55
0.603	95	88.38	6.96

5. EXPERIMENTAL ACTIVITIES AND SIMULATIONS

A simulation work was done using Simulink tool of Matlab to simulate the behaviour of solar cell under different non-normal conditions. The fig. 5-1 shows the model of one solar cell used in the simulation.

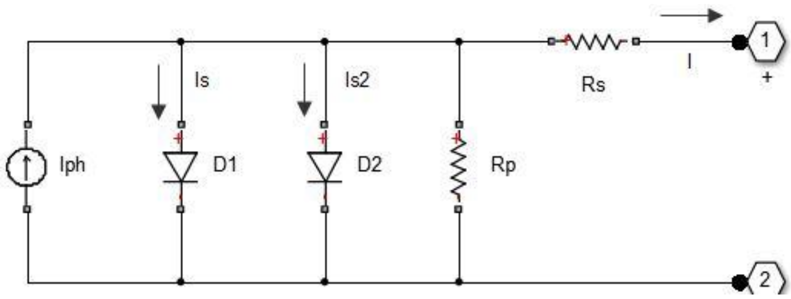


Fig. 5- 1 Modelling of a Solar Cell in Matlab

The governing equation for this model is given as:

$$I = Iph - Is\left\langle \exp\left(\frac{V+IRs}{N*Vt}\right) - 1\right\rangle - Is2\left\langle \exp\left(\frac{V+IRs}{N2*Vt}\right) - 1\right\rangle - \left(\frac{V+IRs}{Rp}\right) \quad (5\text{-}1)$$

where:

- *Is* is the saturation current of the first diode.
- *Is2* is the saturation current of the second diode.
- *Vt* is the thermal voltage, *kT/q*, where:
- *k* is the Boltzmann constant.
- *T* is the Device simulation temperature parameter value.
- *q* is the elementary charge on an electron.
- *N* is the quality factor (diode emission coefficient) of the first diode.
- *N2* is the quality factor (diode emission coefficient) of the second diode.
- *V* is the voltage across the solar cell electrical ports.
- The quality factor varies for amorphous cells, and is typically 2 for polycrystalline cells.

In this work, the used model is “Short circuit current and open circuit voltage, 5 parameters” whose parameters values are given in the table below. This model assumes the following simplification in the 8- parameter model

- The inverse saturation current of second diode is zero
- The impedance of the parallel resistor is infinite

Table 5-1 – The parameters of solar cell

S no	Parameters	Value	Unit
1	Short circuit current	0.435	Ampere
2	Open circuit voltage	0.59	Volt
3	Irradiance	1000	Watt/m^2
4	Quality factor	1.3895	
5	Series Resistance	0.005	ohm
6	Temperature	25	Celsius

Fig. 5-2 and fig. 5-3 present the IV and PV curves by simulation for parameters stated in table 5-1

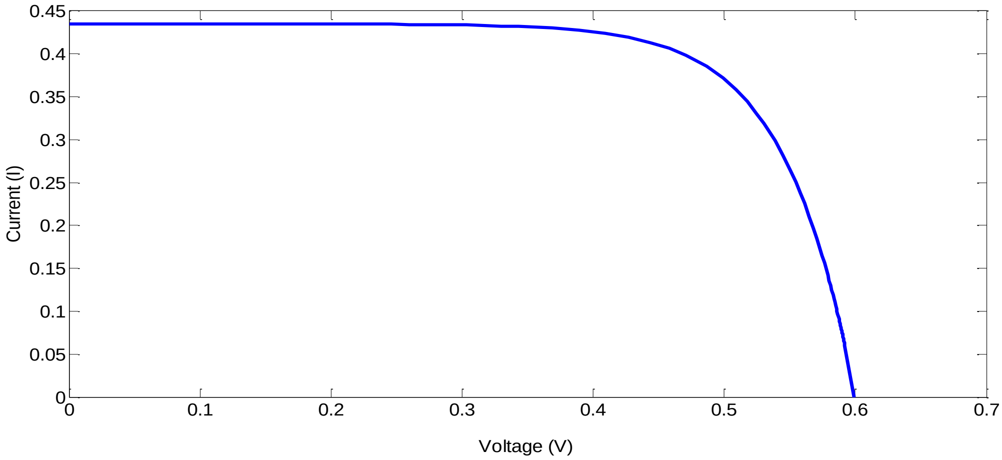


Fig. 5- 2 IV curve of a solar cell

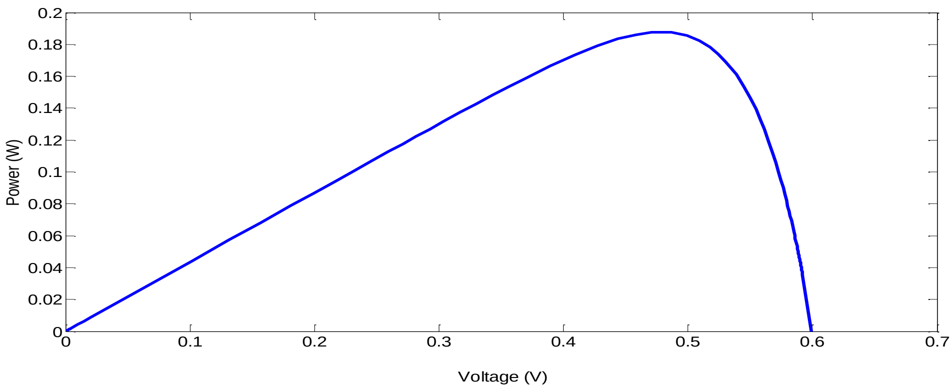


Fig. 5- 3 PV curve of a solar cell

Five tests were performed, of which three were in the laboratory (49, 72 and 128 W / m2 and 28, 29 and 31 ºC) and two outside (406 and 987 W / m2 and 40 and 45 ºC) and the obtained results can be seen in fig 5-4.

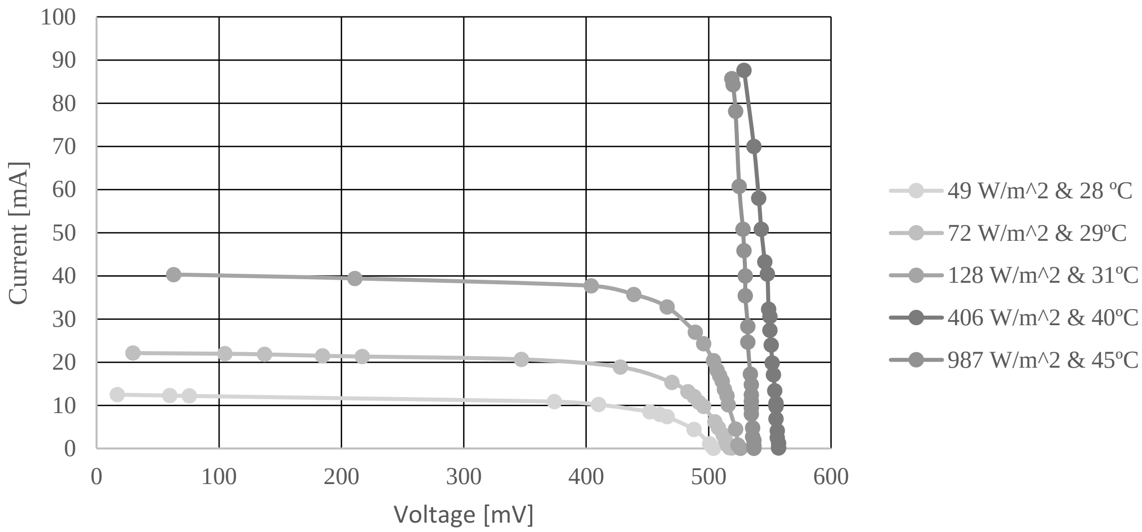


Fig. 5- 4 IV curve of a solar cell in different irradiances

It is possible to verify the typical characteristic of a solar cell with illumination for reduced irradiance. However, as the irradiance increases, it becomes increasingly difficult to determine the short-circuit current. The instrument used here to determine IV curve was the simple rheostat, so it was difficult to determine exact curve with the high irradiance case. Next, the characteristic PV was determined.

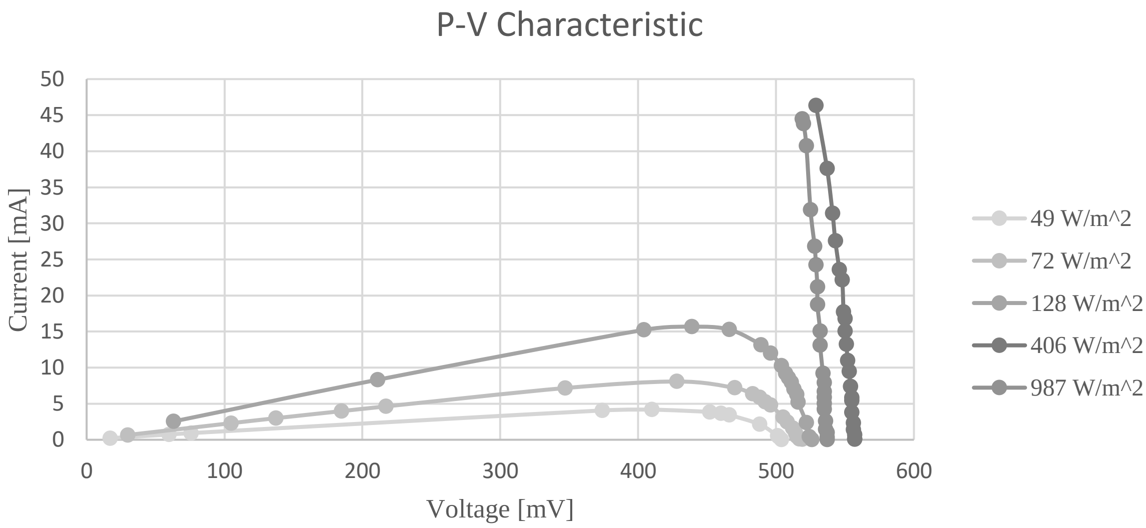


Fig. 5- 5 PV curve of a solar cell in different irradiance

The table 5-2 present the parameter of the solar cell for different conditions. It is known from the Solar Cell Datasheet that the area AC is equal to 34.96 cm2. The results are shown in the following table.

Table 5-2 – Data parameter of a solar cell from experiment

Irradiance[W/m^2]	**49**	**72**	**128**	**406**	**987**
Cell temperature [ºC]	27,5	29,1	31,4	40	45
I_{SC} [mA]	12,5	22,3	40,6		
V_{OC} [mV]	504	519	526	557	537
I_{mp} [mA]	10,2	18,9	35,7		
V_{mp} [mV]	410	428	439		
P_{mp} [mW]	4,2	8,1	15,7		
FF = $\frac{I_{mpp}V_{mpp}}{I_{sc}V_{OC}}$ [%]	66,4	70,4	72,1		
$\eta_1 = \frac{I_{mpp}V_{mpp}}{G*A_C*N}$ [%]	0,7	0,7	0,9		

5.1.1. Effect of series resistance of a solar cell

A general solar cell shows some series resistances. This is due the fact that current must flow through the emitter and base, the contact resistance between the metal contact and silicon and the resistance between the top and rear metal contacts.

The current equation of solar cell is given as:

$$I = Iph - Io\left\{\exp\left(\frac{V+IRs}{N*Vt}\right) - 1\right\} \tag{5-2}$$

Study of the effect of series resistance of the solar cell is done by keeping all the parameters constant and only the series resistance is changed. The obtained result from simulation is shown in the fig. 5-6. From the above equation as the value of the series resistance is increased, there is decreased in the output current from the solar cell, this will result in the decrease in the output power. The open circuit voltage is independent of current flowing through the series resistance so it constant nevertheless there is variation in the series resistances.

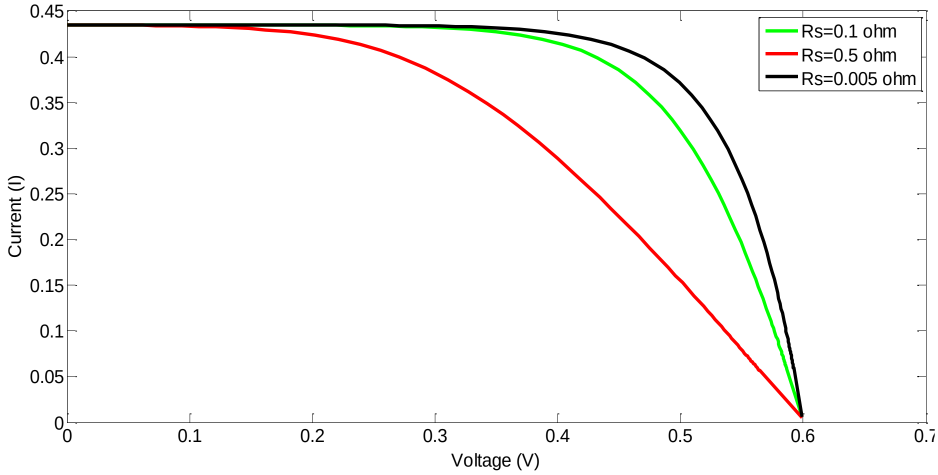


Fig. 5- 6 The effect of series resistance in a solar cell

5.1.2. *Effect of irradiance in the IV characteristics of the solar cell*

The generation of photocurrent from the solar cell is dependent of the solar radiation. The radiation having a certain range of frequency knot out the electron from the bond to the conduction band to form an electron-hole pair [3]. The formation of electron-hole pair is depending upon the intensity of the light i.e. more irradiance more generation of hole pair so this is why the irradiance plays a vital role in the magnitude of generated current.

The relation of the irradiance and the generated current is given as

$$Isc = \frac{G}{Gr} * Isc\_r \tag{5-3}$$

Where

- *Isc*=Short circuit of a solar cell in a irradiance equal to *G*
- *G*= Value of Irradiance at short circuit equal to *Isc*
- *Gr*=Value of irradiance at reference condition i.e. *1000 W/m2*
- *Isc_r*=Value of short circuit current in the reference condition

The effect of the variation in the irradiance is shown in the fig. 5-7. The value of the short circuit current is given by the above equation, but the open circuit voltage is almost independent to the irradiance, it is more dependent on the operating temperature of the cell.

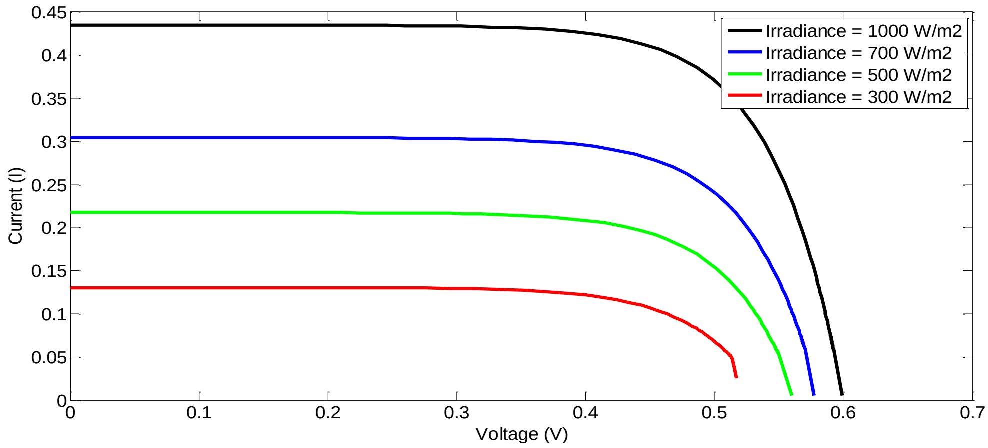


Fig. 5- 7 Effect of irradiance in a solar cell

5.1.3. Effect of temperature on solar cell

The temperature plays a vital role in the performance of a solar cell. The power generated by the PV cell decreased with increment of temperature above the STC condition [31]. Varying with the temperature, the saturation current I_o of diode varies, this inverse saturation current cause change in the solar output current, eventually there is change in the output voltage. The relation between the temperature and inverse saturation current is given by the following equation 5-4. The output of the simulation of PV cell in different temperature is shown in fig 5-8 and fig 5-9.

$$\mathrm{Io} = \mathrm{Iso}\left(\frac{T}{To}\right)^3 \exp\left(\frac{Eg}{m\prime}\right)\left(\frac{1}{Vt\_r} - \frac{1}{Vt}\right) \tag{5-4}$$

Depending upon the irradiance and ambient temperature, the photo current is given by

$$I_L = \frac{G}{G\_r} * I_{Lo} * [C_T\{T - T_0\}] \tag{5-5}$$

Where:

- $Eg = 1.170 - \frac{4.73*10^{\wedge}-4}{T+636} eV$
- $Vt\_r = \frac{k}{q}(273 + 25)$
- G= irradiance (W/m2)
- T= temperature (Kelvin)
- C_T= temperature coefficient of photo generated current
- Is= Inverse saturation current in T (Kelvin) temperature
- Iso= Inverse saturation current in STC condition
- Eg= energy band of semiconductor
- m'= ideality factor of diode

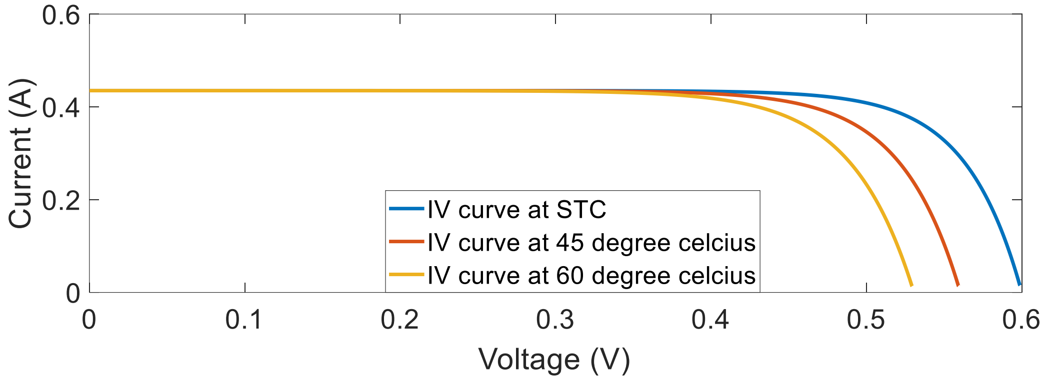


Fig. 5- 8 Effect of temperature on IV curve of a solar cell

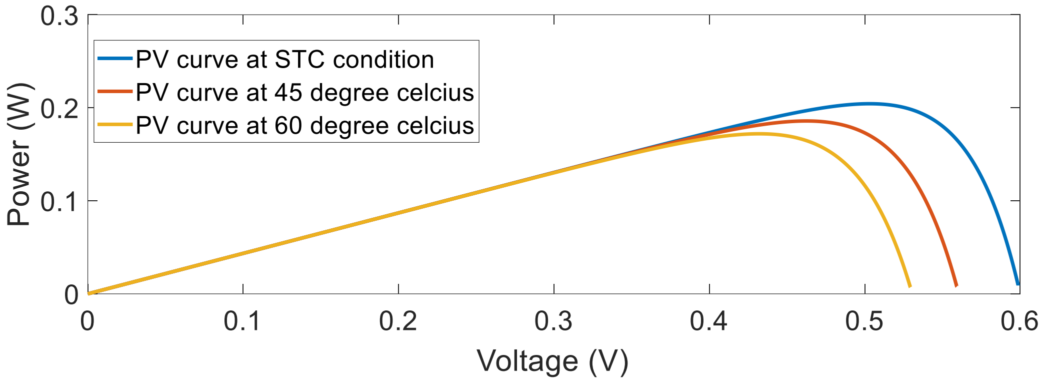


Fig. 5- 9 Effect of Temperature on PV curve of a solar cell

5.1.4. Two cells connected in series

The IV and PV characteristics for two cells connected in series with respect to different irradiance and temperature are shown in the fig. 5-10 and 5-11. From the simulation results it can be concluded that the temperature affects the open-circuit voltage whereas the irradiance affects the short circuit current.

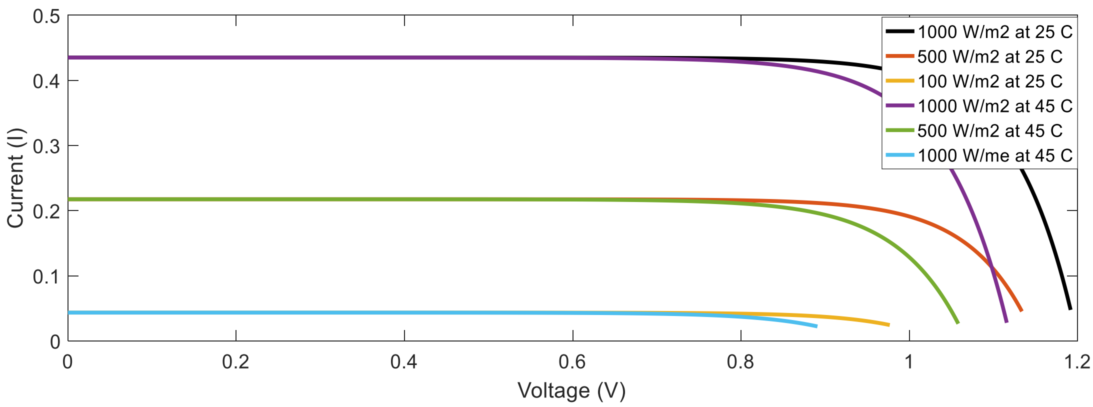


Fig. 5- 10 IV curve of two series connected cells

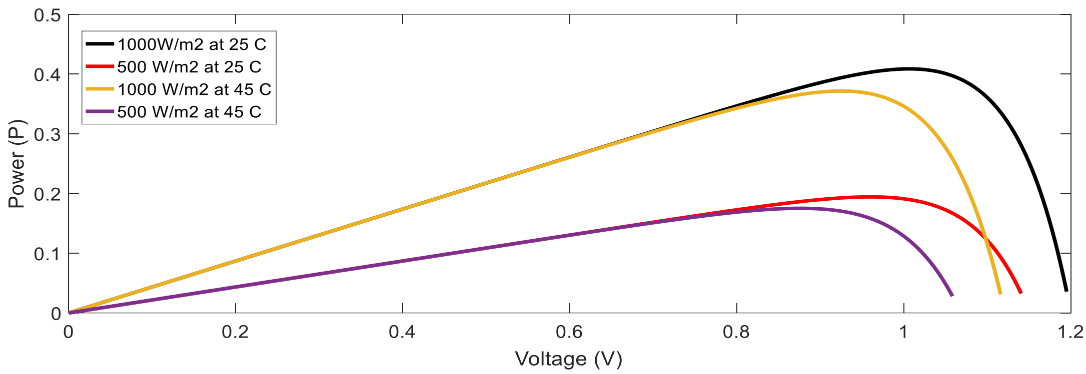


Fig. 5- 11 PV curve of a two series connected cells

The two cells are connected in series and performed the different environmental conditions such as variation in irradiance and temperature. The experimental result is shown in the following figure no 5-9, 5-10 and 5-11. The voltage in series connection is added while the current remains the same since same current must pass through both cells. The experimental tests were done with simple variable rheostat so it was not sufficient to get all the data to characterise the cells in series for higher irradiances. The measurement was very sensitive for high irradiance for low voltage.

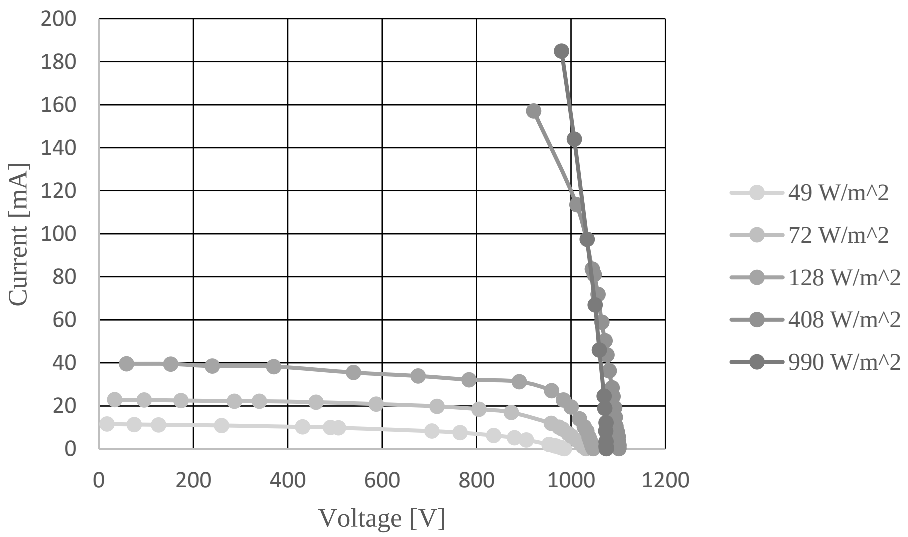


Fig. 5- 12 IV curve of two cells in series

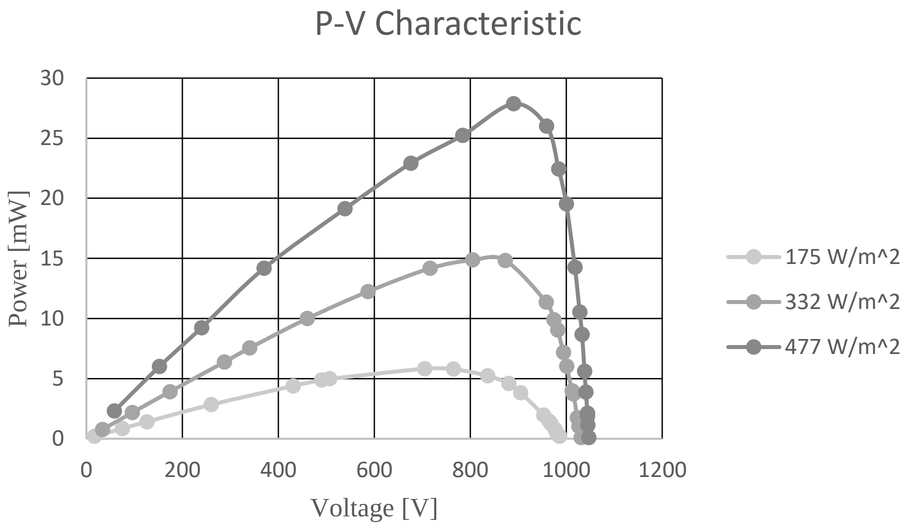


Fig. 5- 13 PV curve of two cells in series

The experiment shows that the short circuit current is highly dependent with the irradiance while the voltage is not so much influence with the temperature. As the irradiance increases the current produced by solar cell increases which can be seen in the table no 5-3. The higher the irradiance, higher the power generation and higher the fill factor of a cell. Due to the inability of the experimental instrument all the required data are not available here.

Table 5-3 – *Parameter of the two cells in series from experiment*

Irradiância [W/m²]	**49**	**72**	**128**	**408**	**990**
Cell temperature [ºC]	27,8	28,8	31,8	40	45
I_{SC} [mA]	11,6	22,9	39,6		
V_{OC} [mV]	986	1031	1047	1101	1075
I_{mp} [mA]	8,3	18,5	31,3		
V_{mp} [mV]	705	805	890		
P_{mp} [mW]	5,8	14,9	27,9		
FF = $\frac{I_{mpp}V_{mpp}}{I_{sc}V_{OC}}$ [%]	51,1	63,1	67,2		
$\eta_1 = \frac{I_{mpp}V_{mpp}}{G*A_C*N}$ [%]	0,5	0,6	0,8		

5.1.5. Effect of mismatch of the current

Mismatch of the current, produced by different cells in series makes adverse effect in the overall generation of the power. It causes the current produced by the one cell having large current is limited by another cell producing the less current. It doesn't have significant effect on the voltage.The reason for the cause of mismatch is not specific fault, it may appear by some error in the time of manufacturing, partial shading, non-uniform temperature [21], dust or soiling etc. The result of simulation of mismatch of solar cell can be seen in the fig. 5-14. The data of a solar cell for the simulation is given in the table 5-4.

Table 5-4 – Solar cell data

	Isc (A)	Voc (V)
Cell 1	0.435	0.59
Cell 2	0.435	0.59
Cell 3	0.335	0.59

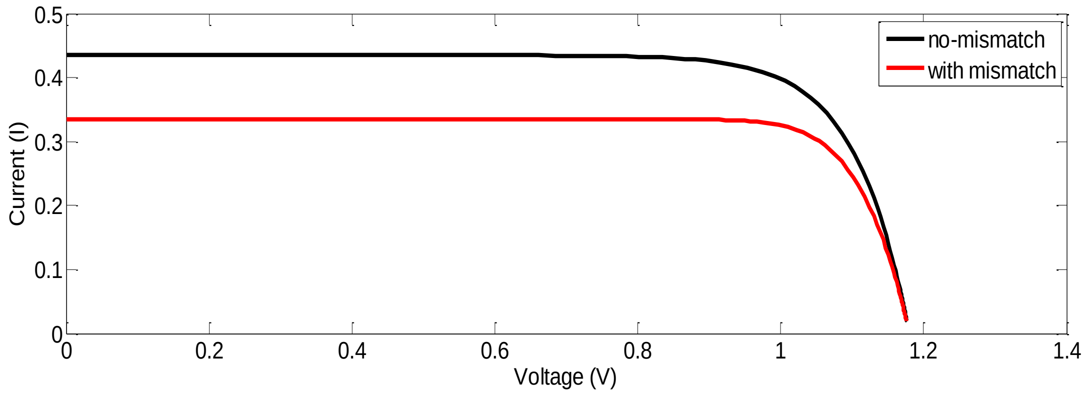


Fig. 5- 14 Effect of mismatch current

5.2. Effect of shading on a group of a solar cell

Shading on a group of cells will reduce the total generated power output of the panel by two reasons; it reduces the input energy and increases losses in the shaded cell. Shading is also responsible for creation of hotspot, which consequently increases the cell power dissipation and aging and eventual damage of the device [32].

Let us consider a situation of fig. 5-15 which represents a string with two solar cells. One cell is under full illumination and the second is partially shaded. The current generated under full illumination is Iph and the current generated under the partial illumination is Iph, sh. To study the effect of shading let us consider a ratio of current generated by shaded cell to fully illuminated cell is represented by F, then F=0 means fully shaded and F=1 means fully illuminated. Assuming a cell partially shaded and that the leakage resistance values are not much effected due to partial shading and illumination, the cell under shading is obtained, the current is given by

$$I = Iph - Is \langle \exp\left(\frac{V+IRs}{N*Vt}\right) - 1\rangle - \left(\frac{V+IRs}{Rp}\right) \qquad (5\text{-}6)$$

$$I = FIph - Is \langle \exp\left(\frac{Vsh+IshRs}{N*Vt}\right) - 1\rangle - \left(\frac{Vsh+IshRs}{Rp}\right) \qquad (5\text{-}7)$$

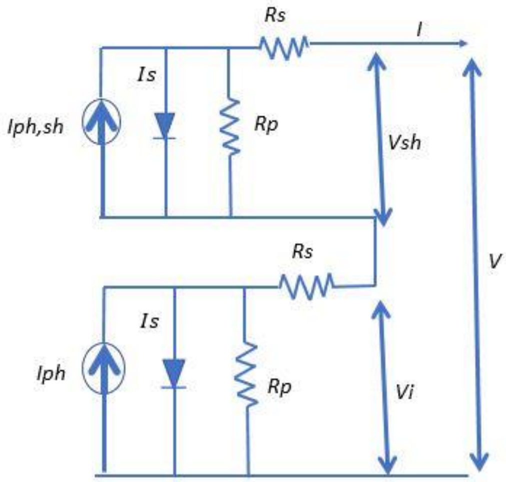


Fig. 5- 15 Schematic model of two cells in series

As the extent of shading increases, the exponential term tends to zero [32] and hence the shaded cell voltage and voltage across string can be approximated as

$$Vsh = (Flph, sh - I) + IRs \tag{5-8}$$

$$V = Vi + Vsh \tag{5-9}$$

Finally, the power dissipated by the shaded cell may be obtained as

$$Pdis = I\{(Flph, sh - I) + IRs\} \tag{5-10}$$

The effect of shading is studied with the help of three solar cells, they are connected in series and performed different simulation to study of the shading effect on the output IV curve of the group of a cell. In this simulation, the first case is the normal uniform irradiance in all cell of 1000W/m2. In the second case, the irradiance is kept constant for two outsider's cells and the middle one was given 700W/m2, without bypass diode, and in final case the bypass diode is used as shown in the fig. 5-16

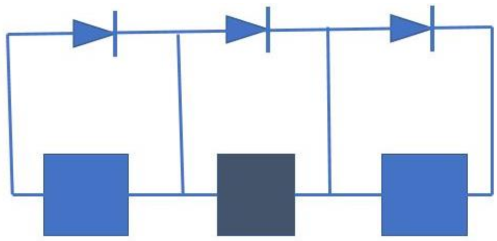


Fig. 5- 16Three cells in series connection

Table 5-5 – Simulation of 3 cells

Case	**Irradiance**		
	Cell A	Cell B	Cell C
Case A (normal)	1000	1000	1000
Case B	1000	700	1000

The fig. 5-17 below shows the output characteristics of the shading case as described above. The bypass diode plays vital role in case of shading as it provide the path for the power produced by the adjacent cell when the cell is shaded.

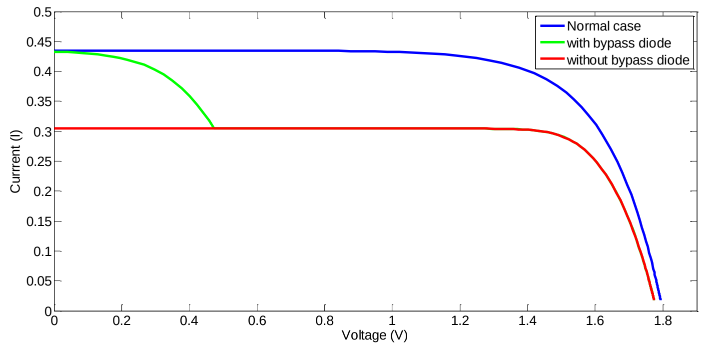


Fig. 5- 17 The effect of shading on three cells

For the further study of the shading effect on a group of cells more simulations work has been presented. Fig.5-18 shows a simple configuration of solar cells combining them into two groups having a different number of cells in a group. This configuration helps to study the characteristics of cells when they are exposed for partial shading. The cell shown in black is simulated for various level of irradiance and obtained the IV and PV curve shown in fig.5-19 and fig 5-20. The shaded cell has reduced the value of the current of series-connected cell in accordance to the irradiance, this results in the drastic change in the output power of the configuration.

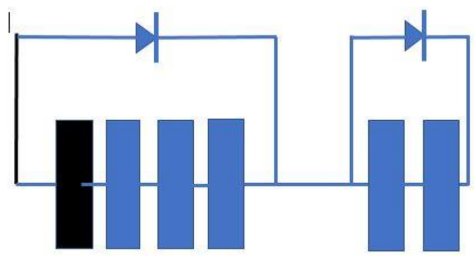


Fig. 5- 18 Shading case I

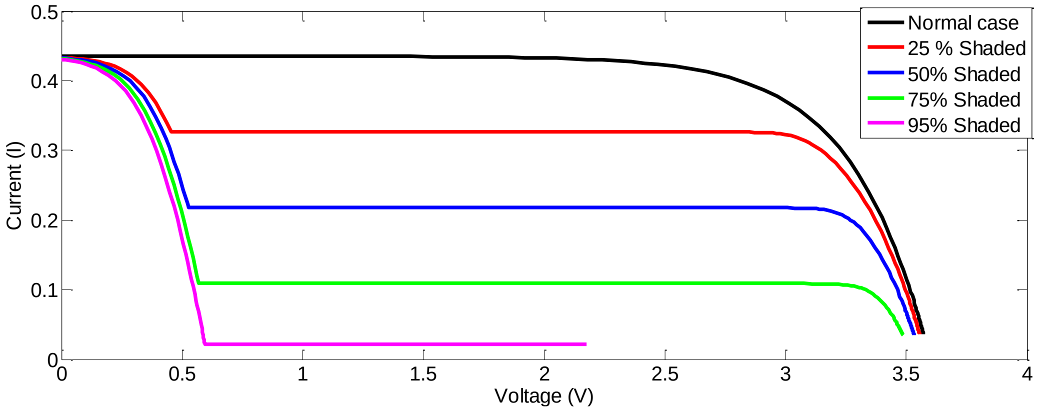


Fig. 5- 19 IV curve of group of solar cells presented in fig. 5-18

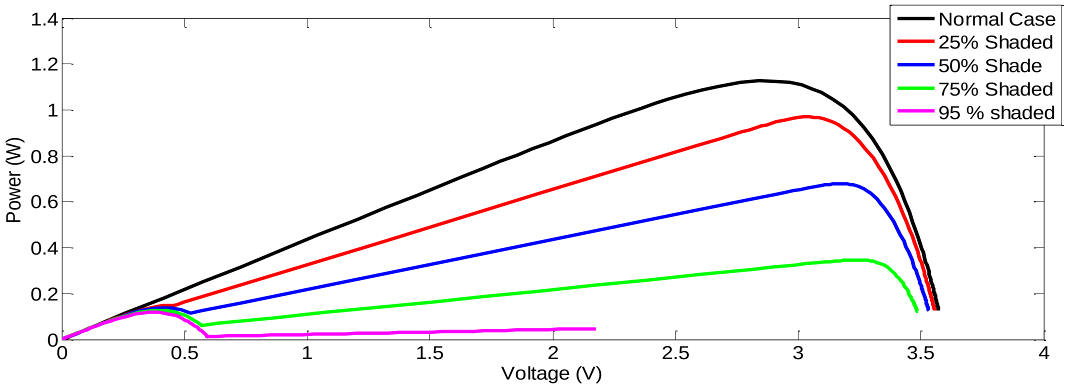


Fig. 5- 20 PV curve of group of solar cells presented in fig. 5-18

The fig. 5-21 shows another configuration for the study of shading effect on a cell in a group. The configuration is same as the previous only the shading effect is changed to a cell of another group. The fig. 5-22 and fig. 5-23 show the simulation result for the different level of irradiance. The presence of bypass diode across the cell gives more peak points of power. In the previous case, a single shaded cell has limited the current through the whole group, in this case, the shaded cell has only one adjacent cell, so the power loss is less compared to the previous case.

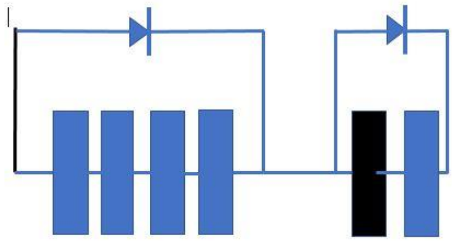


Fig. 5- 21 Shading case II

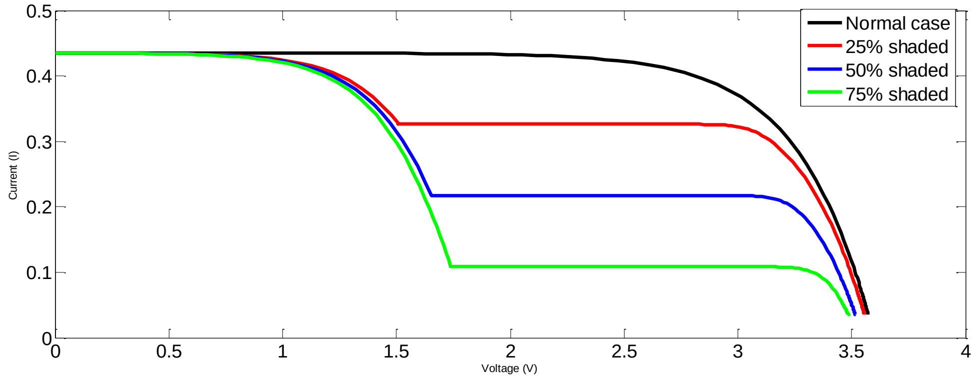


Fig. 5- 22 IV curve of shading case II

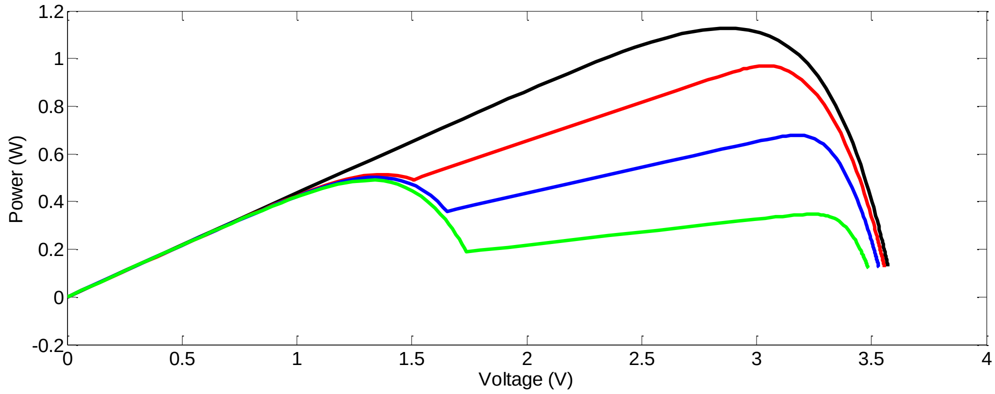


Fig. 5- 23 PV curve of shading case II

The study of shading effect is furthermore extended with the cells having partial shading on both groups. This the extreme case, as it causes drastically reduction of the power production. The table 5-6 shows the scenario regarding the shading cases. The no shading case means STC conditions and consecutive cases are the percentage of available irradiance of STC. The generation of current from normal cells is limited by shaded cells give unprecedented loss in power can be seen in fig. 5-25 and fig 5-26

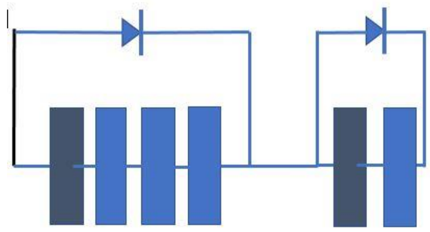


Fig. 5- 24 Shading case III

Table 5-6 – *Shading data*

Data	Shading on cell A	Shading on cell B
Data1	0%	0%
Data3	25%	50%
Data3	25%	75%
Data4	50%	50%
Data5	75%	25%

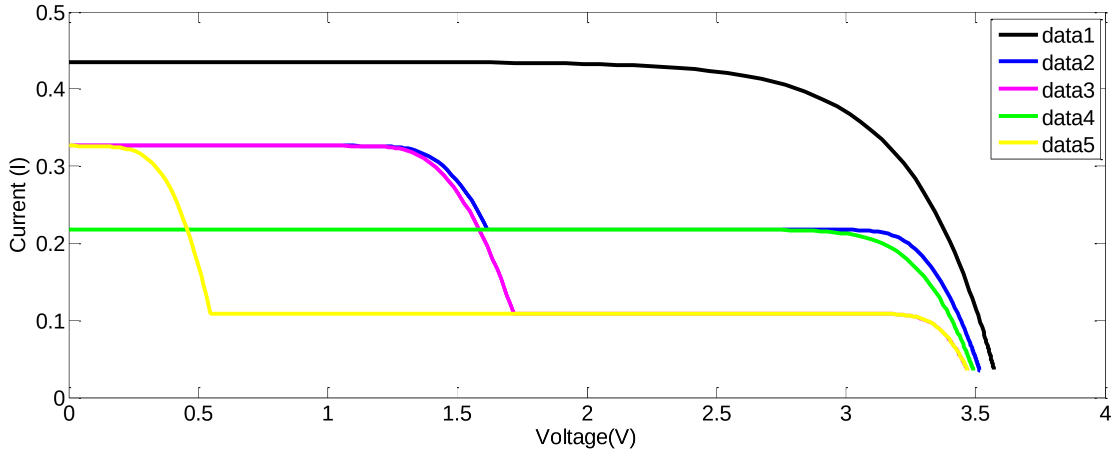


Fig. 5- 25 IV curve of shading case III

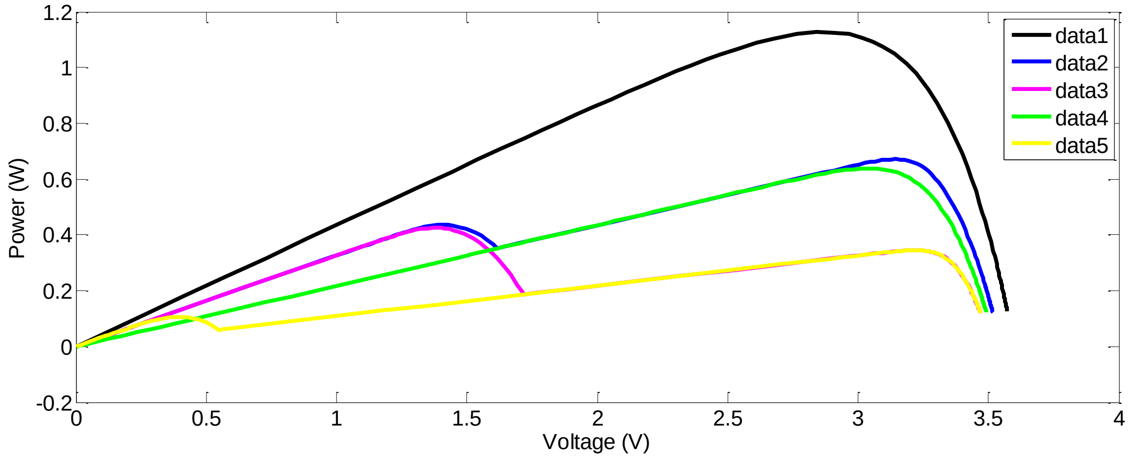


Fig. 5- 26 PV curve of shading case III

5.3. Faults on group of cells (string) module

The module is prone to various faults, the different types of faults. The module consists of the group of cells connected parallel and series with the help of the bypass diode. The module faults may occur due to faults on cells, bypass diode, and connecting wires. The various types of faults on the cells are already described in the above section. Some faults due to bypass diode are also described earlier but then here the influence of bypass diode fault is also mentioned in this section. The table 5-7 show the data parameter for the simulation. The fig 5-27 shows the configuration of cells building a module.

Table 5-7 – Parameters of model

Sno	Descriptions	Value
1	No of cells	96
2	No of cells in series	12
3	No of cells in parallel	8
4	I_sc of each cell	0.435 A
5	V_oc of each cell	0.6 V
6	I_sc of Module	3.48 A
7	V_oc of Module	4.8 V

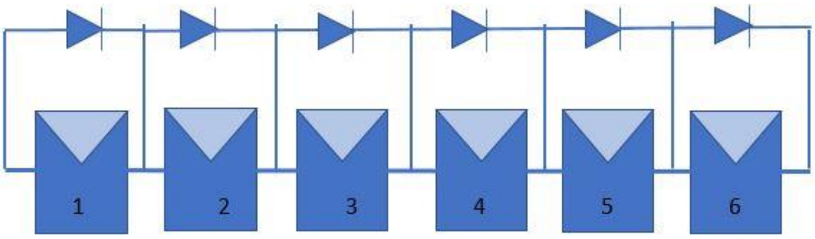


Fig. 5- 27 Schematic design of a PV module

5.3.1. *Faults on a bypass diode*

A bypass diode is wired parallel with an individual group of cells to provide a current path in case the cell (or module) becomes faulty or open circuited. One of the main technologies used by PV panels to mitigate the shading effects consists the use of electronic devices, bypass diodes. The use of bypass diodes allows a series of connected cell to continue supplying power at a reduced voltage rather than no power at all. The bypass diode is connected in reverse bias condition between the group of cells. Ideally, there would be one bypass diode for each cell but it is too much expensive, so there is a diode for each group of cells.

5.3.2. *Short circuit of a bypass diode*

A bypass diode used in a module can get faulted, can provide the short circuit path to the module. The figure 12 shows the simulation result of a short-circuited bypass diode in any group of cells. The short-circuited bypass diode has provided the short path and exclude the power generated by the adjacent cells which is clearly seen in the fig 5-28. The short circuit of a bypass diode leads to loss of power equivalent to how much it has shunted to. In this case a short circuit in bypass diode has decreased 16% of the total power generated by whole system.

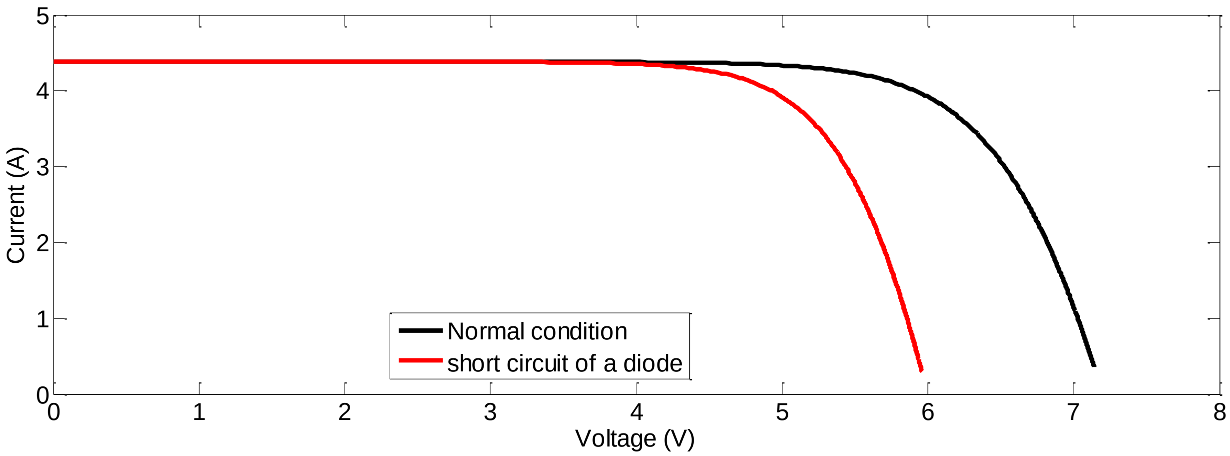


Fig. 5- 28 Effect of short circuit of bypass diode

5.3.3. *Bypass diode act as resistance*

A bypass diode cannot have practically zero resistance but can have some resistances. Sometimes it can act like resistance, providing the bypass path to the current flowing through circuit. As there is presence of some resistances there is power dissipation in the resistances of diode and the output can be changed. Lower the value of resistance more current will flow it and vice versa. The fig. 5-29 present the output IV curves of the PV module according to the different resistances present in the bypass diode.

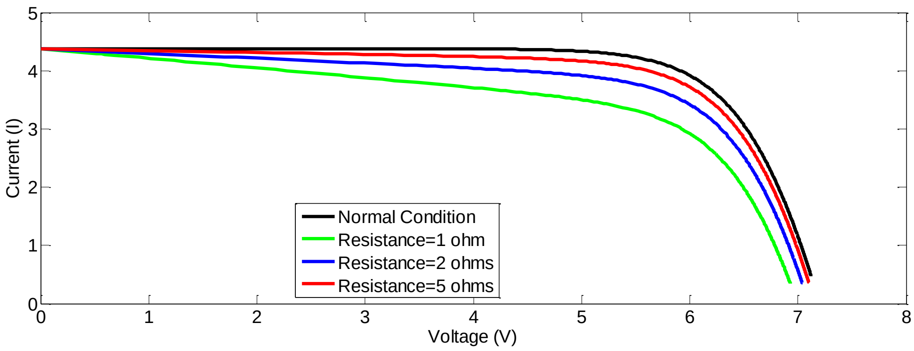


Fig. 5- 29 Effect of resistance of bypass diode

5.3.4. *Reversal of bypass diode*

A bypass diode may be kept reversal mistakenly, so it is necessary to simulate the effect of reversal of bypass diode. The result of the simulation shown in the fig. 5-30. The reversal of the bypass diode caused the decreased in the open circuit voltage as the bypass diode provides the path for the circulation of the current. Eventually it leads to power loss equivalent to how much cell it has shunted.

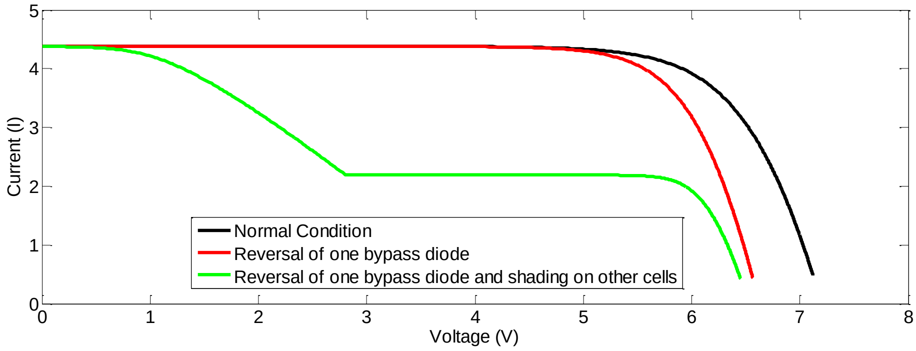


Fig. 5- 30 Reversal of a bypass diode

5.3.5. *Simulation of module of three group of cells*

The data for the following PV modules are present in the below table 5-8 and output curve can be seen in fig. 5-31. The table 5-9 presents power available in the different non-normal conditions. The major power loss occurs during shading followed by fault in bypass diode and increase in series resistance.

Table 5-8 – *Datasheet of a PV String*

Sno	Description	Value
1	Open circuit voltage (Voc)	38.5 V
2	Short ciruit current (Isc)	9.43 A
3	Voltage at maximum power (Vmp)	31.5 V
4	Current at maximum power (Imp)	8.89 A
5	Temperature coeffcient of Voc	-0.31 V/K
6	Temperature coefficient of Isc	-0.053 A/K

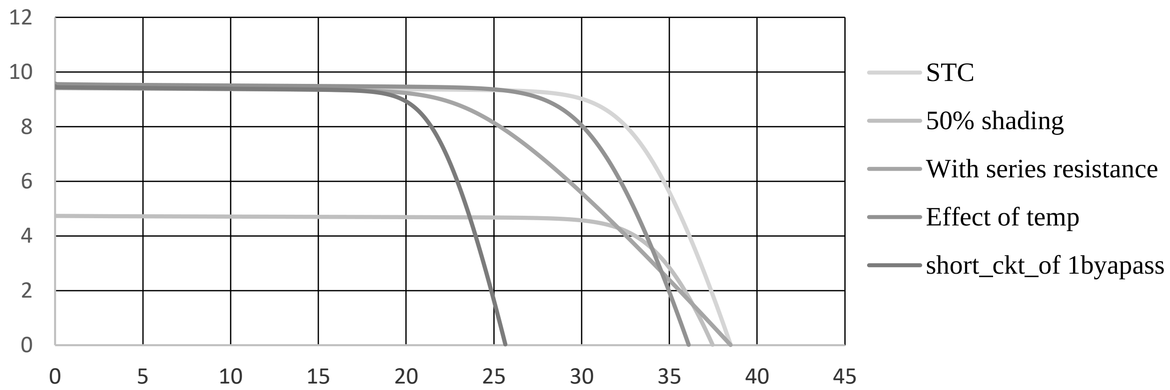


Fig. 5- 31 IV curves of PV panel in different working conditions

Table 5-9 – Power available in the different non-normal conditions

Sno	Condition	Power Available (W)	Power avaliable (%)	Power lost (%)
1	STC	271.7	100	0
2	50% Shading	138.8	51.11	48.8
3	Series resistance (0.5 Ω)	204.1	75.13	24.8
4	Effect of temp (60 °C)	250.7	92.27	7.7
5	Short circuit of 1 BP diode	178.6	65.74	34.2

5.3.6. Experiment on Module

This experiment was conducted on the 225W Polycrystalline Solar Module located on the roof of the IST south tower. The electrical characteristics of this solar panel can be found on the data sheet contained in Appendix 1. A schematic and photo of the testing apparatus is shown in Figure 5-32.

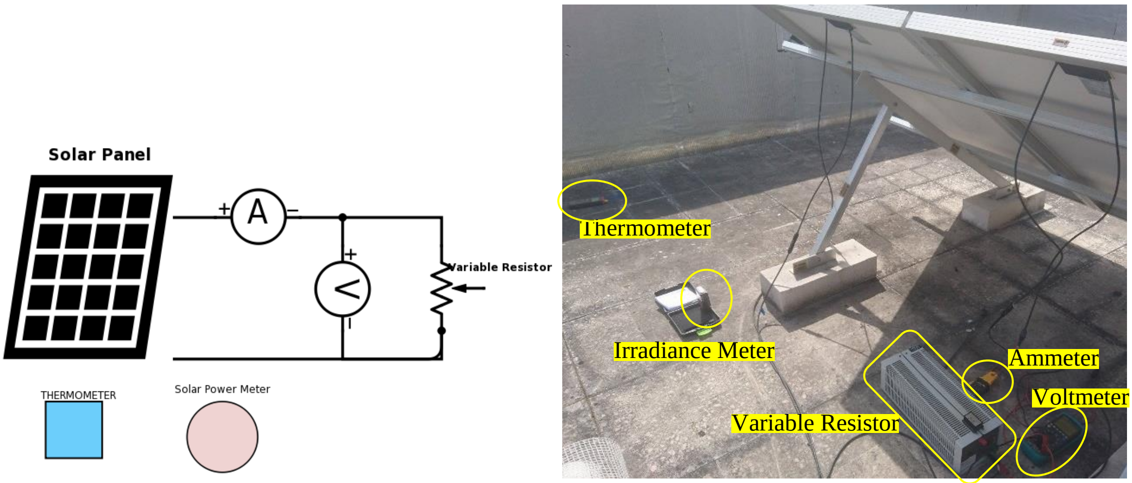


Fig. 5- 32 Schematic and Setup of IV measurement on IST roof

The IV curves were measured for different irradiances, temperatures and with different covers to replicate clouding and faults in the solar panel. The scenarios tested are shown in table 5-10.

Table 5-10 – Conditions tested on the solar panel

Scenario	**Atmospheric conditions**	**Cover**
A – No Cover	Average Irradiance (G) – 705W/m^2 T_{atm} - 24°C T_{cell} - 46°C	
B – No Cover	Average Irradiance (G) – 890W/m^2 T_{atm} - 32°C T_{cell} - 60°C	
C – White Grate	Average Irradiance (G) – 705W/m^2 T_{atm} - 24°C T_{cell} - 46°C	

D – Bubble Wrap	Average Irradiance (G) – 875W/m^2 T_{atm} – 31.5°C T_{cell} - 59°C	
E – 2/3rds covered	Average Irradiance (G) – 820W/m^2 T_{atm} - 25°C T_{cell} - 51°C	
F – 2/3rds covered	Average Irradiance (G) – 900W/m^2 T_{atm} - 32°C T_{cell} - 60°C	
G – 1/3rd covered	Average Irradiance (G) – 800W/m^2 T_{atm} - 26°C T_{cell} - 51°C	
H – 1 Square covered	Average Irradiance (G) – 810W/m^2 T_{atm} – 24.5°C T_{cell} - 50°C	

I – Bottom half covered	Average Irradiance (G) – 770W/m^2 T_{atm} – 24.5°C T_{cell} - 49°C	

The different experimental scenario shows different IV characteristic of the panel. The first experiment was done for normal (No cover) case with different in temperature and irradiance, it gives the normal IV curve but higher short circuit in higher irradiance which can be seen in the figure 6-30. Similarly, in the case C and D a transparent sheet is used to covet the panel but with different manner once with fine wrap and another with bubble wrap, in this scenario there is no such significant difference in these two scenarios. The case E, F and G present the case of the shading (1/3 and 2/3), the shading cause the evolution of notches in the IV curves, higher the shading region, lower will be the power. The case H represents where only one cell is shaded completely, this give the IV curve as in the case G, this is the that this cell is connected series with other cell and there no way for current to flow from its group of cells. The last case, I is the case where shading is done for bottom part of the panel, since the cell of the panel are connected series (upside-down), there no way for the flow of the current, so this gives the no power to output of the system which can be seen in the fig 5-33. [Source:**]

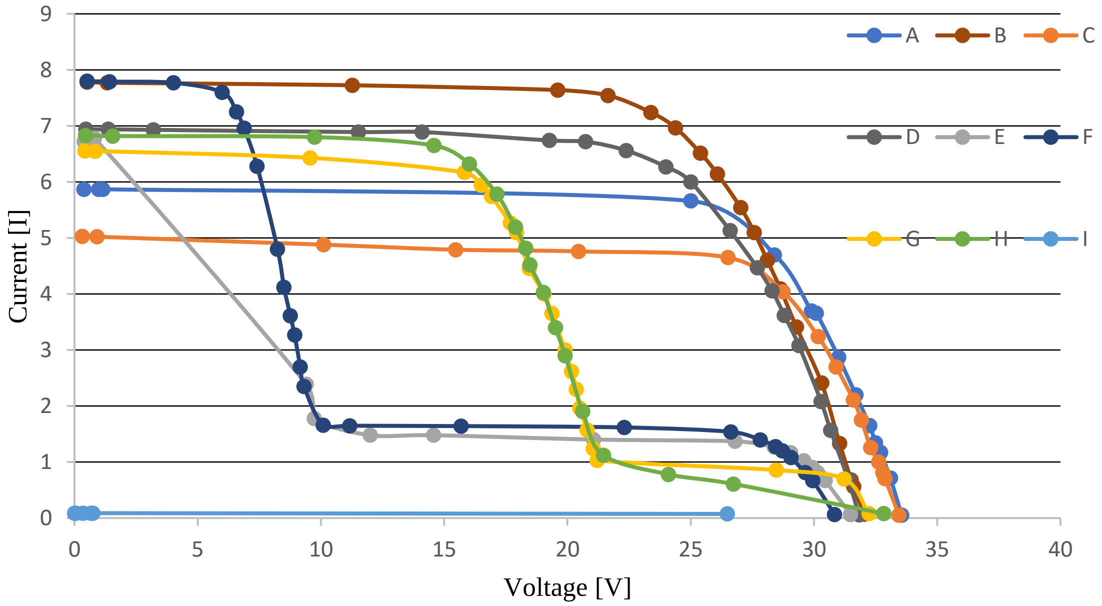


Fig. 5- 33 Curves measured on a solar panel under different scenarios

5.4. Fault on a String of modules

5.4.1. Effect of Partial shading

The major fault or non-operating condition of PV string is the partial shading. Simulaton clearly shows how the different irradiance effects the output of characteristics of a system. Here, the three number of panels are connected in series and they are exposed to different irradiance but each panel has uniform irradiance, this gives the condition of partial shading. The output IV and PV graph are presented below. The partial shading causes high output power reduction in the operation of MPPT.

A bypass diode used in a module can get faulted and provide the short circuit path to the module. Fig 5-28 shows the simulation result of a short-circuited bypass diode in any group of cells. The short-circuited bypass diode has provided the short path and exclude the power generated by the adjacent cells which are clearly seen in the fig 5-34.

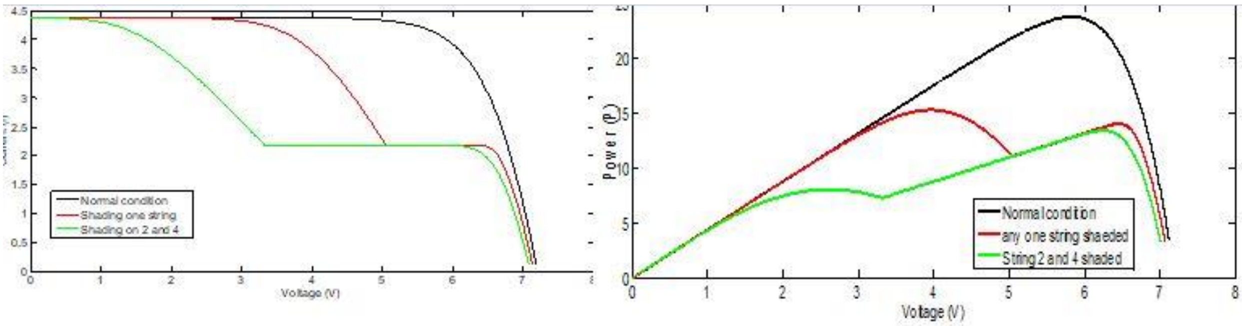


Fig. 5- 34 Effect of shading on IV and PV curve

For the further study of the partial shading and other expected faults, a model is designed for the simulations and experiments. The data parameter of module is given in table 5-11. The data presented in the table 5-10 is the overall value of system not of a single module. The different faults are simulated individually and graphs has presented. The fig 5-35 shows the simulation configuration for Matlab where three modules are connected in series and fig. 5-36 shows the output of IV and PV curve of simulation.

Table 5-11 – Datasheet of a PV module

Sno	Description	Value
1	Open circuit voltage (Voc)	38.5 V
2	Short ciruit current (Isc)	9.43 A
3	Voltage at maximum power (Vmp)	31.5 V
4	Current at maximum power (Imp)	8.89 A
5	Temperature coeff of Voc	-0.31 V/K
6	Temperature of Isc	-0.053 A/K

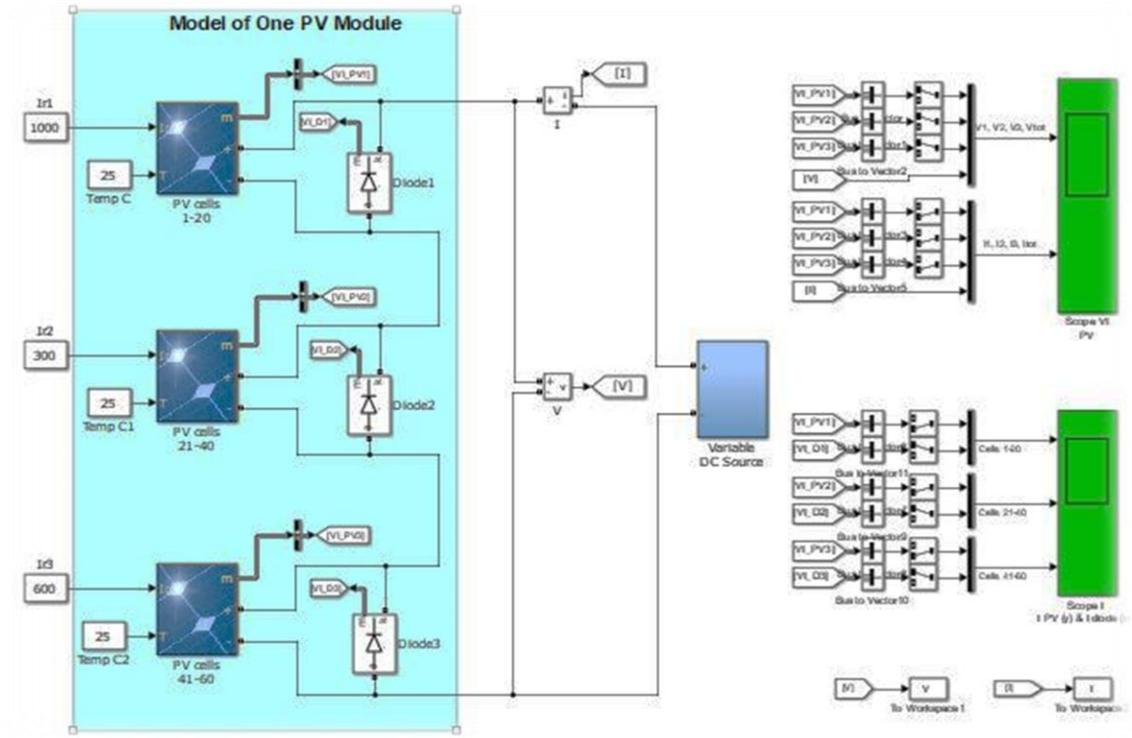


Fig. 5- 35 Simulation configuration for partial shading

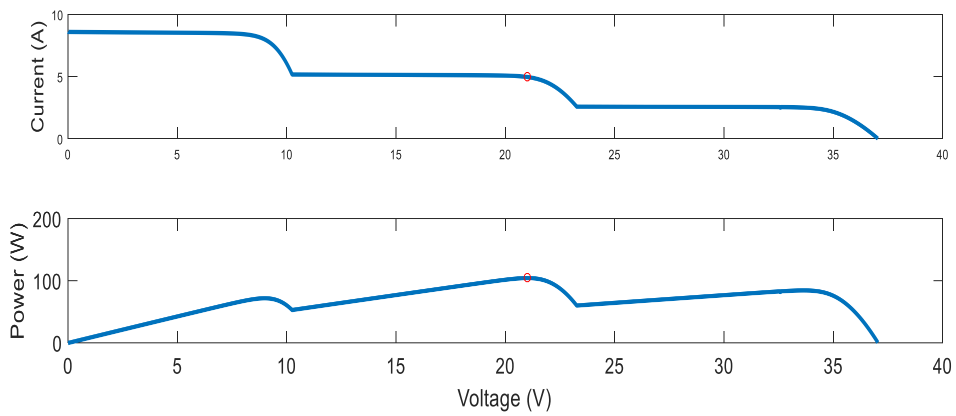


Fig. 5- 36 IV and PV curves of 3 modules connected in series

5.4.2. Open voltage fault on a array of PV

The simulation is carried out for the different faults for the PV system. The fig. 5-37 is the representation of the PV string having three modules in parallel. In this simulation, the fault is on the middle module it is no supplying the power due to fault in the diode or the connection problem. The data parameters are the same as the above module. The graph from simulation is shown in the following fig. 6-38 and 6-39. Table 5-12 shows power loss in this scenario, the loss of one whole PV module.

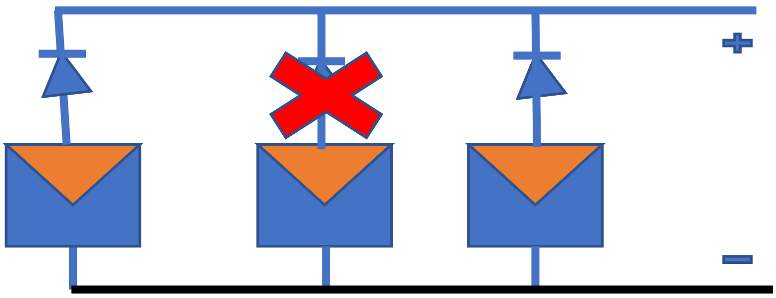


Fig. 5- 37 String of PV modules

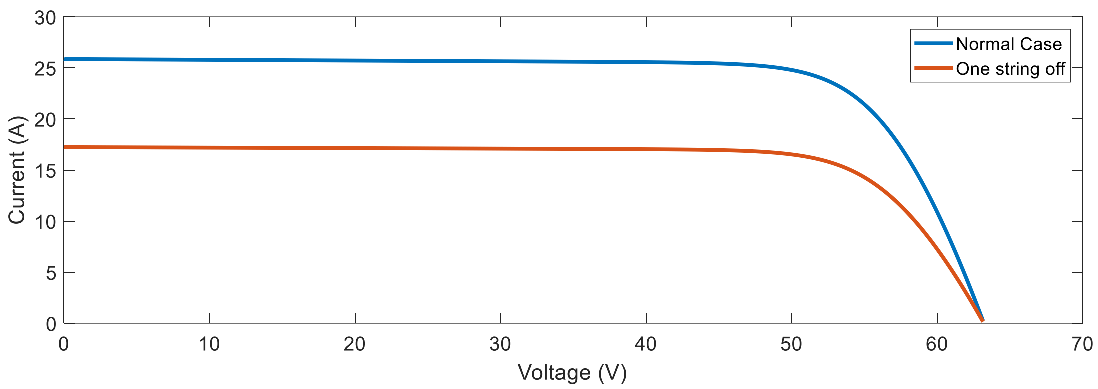


Fig. 5- 38 IV curve of string of PV

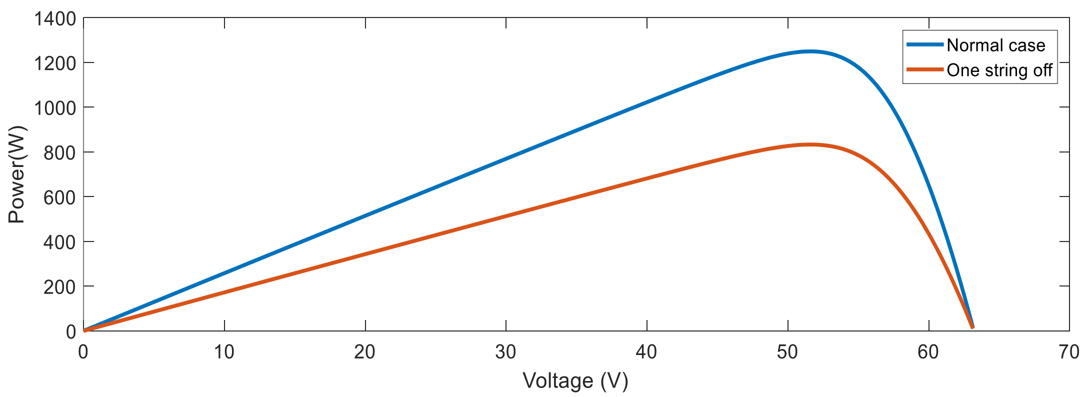


Fig. 5- 39 PV curve of a PV string

Table 5-12 – *Comparison of power between normal and open voltage fault case*

sno	Power in normal case (W)	Power in fault case (W)	Power available (%)
1	1249.1	832.78	66.6

5.4.3. Degradation of PV string

The degradation of the PV module occurs because of the continues exposers in the various environmental conditions. It has to withstands the rains, hailstone, dust particles, ultra violet rays [21] etc. This kind of degradation leads to the increase in the series resistances as shown in figure 5-40. The degradation is simulated as the increment of the series resistance (0.5 Ω in 10 years) in a module and simulation is carried out. From the simulation, the power degradation of PV module can be calculated. The comparison of IV and PV curves between this time interval can be seen in fig 5-41 and 5-42. From this simulation the power decrement for 10 years of time is 7.75%. This is not the precise value but it can be taken as reference. The value is given in the table below 5-13.

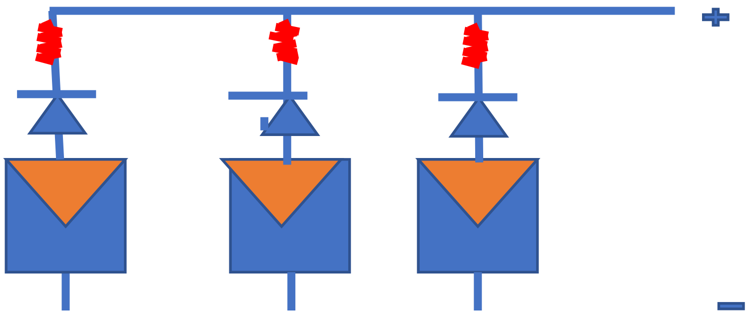


Fig. 5- 40 Strings of PV modules

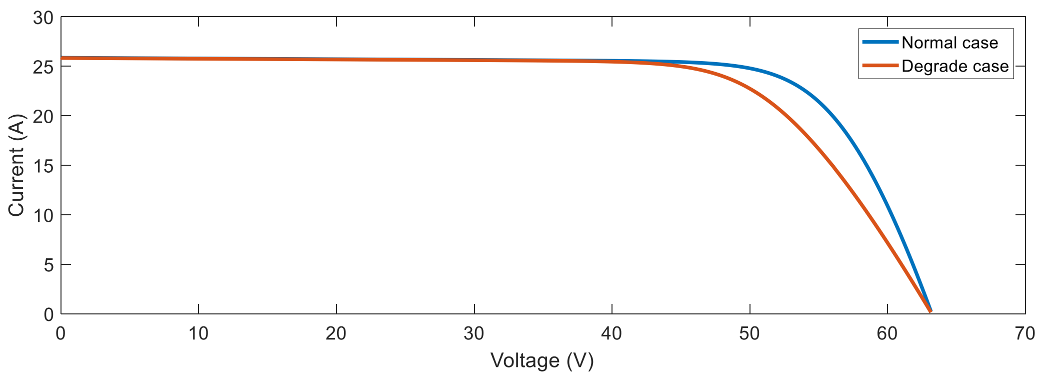


Fig. 5- 41 IV curve of a string

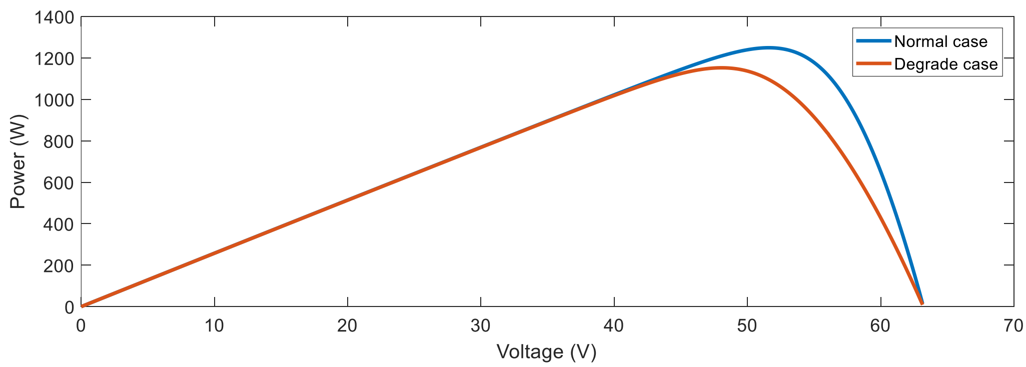


Fig. 5- 42 PV curve of a string

Table 5-13 – Comparison of power before and after degradation of PV panel

sno	Power in Normal condition (W)	Power with degradion (W)	Power available (%)
1	1249.18	1152.3	92.

6. ALGORITHM FOR FAULT DETECTION

The objective of this chapter is to develop an algorithm for the detection and localization of the fault in the PV system. The algorithm [19] developed here is based on the analysis of the IV characteristics of the PV system. This method first develops the IV characteristics for the list of fault scenarios and stores in the memory and access the memory as per required. At the time of a fault, the faulted IV characteristics are then compared with the each stored IV characteristics, find the most resembling characteristics and this is how it recognizes the type of fault and where it is located. The prior knowledge of the faulted condition can be established using the simulation programs like Matlab or Labview. The simulation of the faulted conditions provides the symptoms of the fault. These symptoms will help to diagnose the type of fault and the location of a fault.

6.1. Symptoms for detection of fault

6.1.1. Establishment of a knowledge of the different faults

For the detection of the type of a fault it is necessary to establish the knowledge of characteristics of the different kinds of faults that can occur in the PV system. It is carried out by the series of simulations that must be performed for all the probable faults that can occur in the system. The results of the series of the simulation is thus recorded for the future reference.

6.1.2. Establishment of the simulation scenario

The characteristics symptom for the detection of fault is determined by the simulation for each type of fault. There are three factor that should be considered for the simulation they are the severity of the defect, the variation of the operating condition and the PV configuration system (module/string).

6.1.3. Severity of defect

The severity of most defect can be defined by two quantities a) amplitude and b) the number of component in fault condition. “X” represents the consequences of fault that can only quantified with the number of faulty components. The table 6-1 shows the list of types of faults and its signature consequences.

Table 6-1 – List of types of faults and its consequences

Type of faults	Faults	Results (Consequences)
Mismatch faults	Shading	Iph (decreases)
	Series resistance	Rs(increases)
	Resistance	Rp(increases)
	Temperature	T increases
Bypass diode faults	Short circuit	X
	Disconnection	X
	Reverse connection	X
	Possess resistance	R (increases)
Module faults	Short circuit of Module	X
	Shunt of Module	Rm (increases)
	Inversion of Module	X
Connection faults	Resistance due to connection	X
	Disconnection	Rm (increases)
Non-return diode faults	Short circuit	X
	Module shunt	Rm (increases)
	Disconnection	X
	Reverse connection	X

6.1.4. Variation in the operating condition

Environmental variation has great influence on the performance of the PV system. The module temperature, incident irradiance, and spectral irradiance are the important factor [31]. The operating temperature of the solar module plays a central role hence the efficiency and power output of a PV module depends on the operating temperature [31]. For the simulation, there should be different operating conditions scenario. There should be different irradiance with the difference in temperature. The different weather condition should be applied to the simulation then only it is valid for the characterization of the fault condition according to the environment.

6.1.5. Configuration of the system

There are basically three levels of the PV system (group of cells, module, array, or string). The IV characteristics of each level is different from another level. The cumulative curve of cell gives rise to the module and the cumulative curve of module gives the curve of array. For the detection of location of the fault it is necessary to record the IV characteristics of the fault condition of each level of the P-V system.

6.2. Identification of symptoms

The result of simulations of the different faults in the PV system is shown in the fig 6-1. This figure gives the potential symptoms of different faults associated with PV system [19]. Any fault can generate several symptoms, but some symptoms are common to several faults. Therefore, the detailed studies should be carried out to figure out the exact fault in the system. Basically, there are four zones that can be affected by the fault in the PV system. The first zone is the zone 1, is a zone of the open circuit voltage. Zone 2 is the zone of the short circuit current. Similarly, zone 3 is the zone of in between the open circuit voltage and short circuit current. Finally, zone 4 represent the slope of either short-circuit current or open circuit voltage. Table 6-2 presents the symptoms, its effecting area and its consequences.

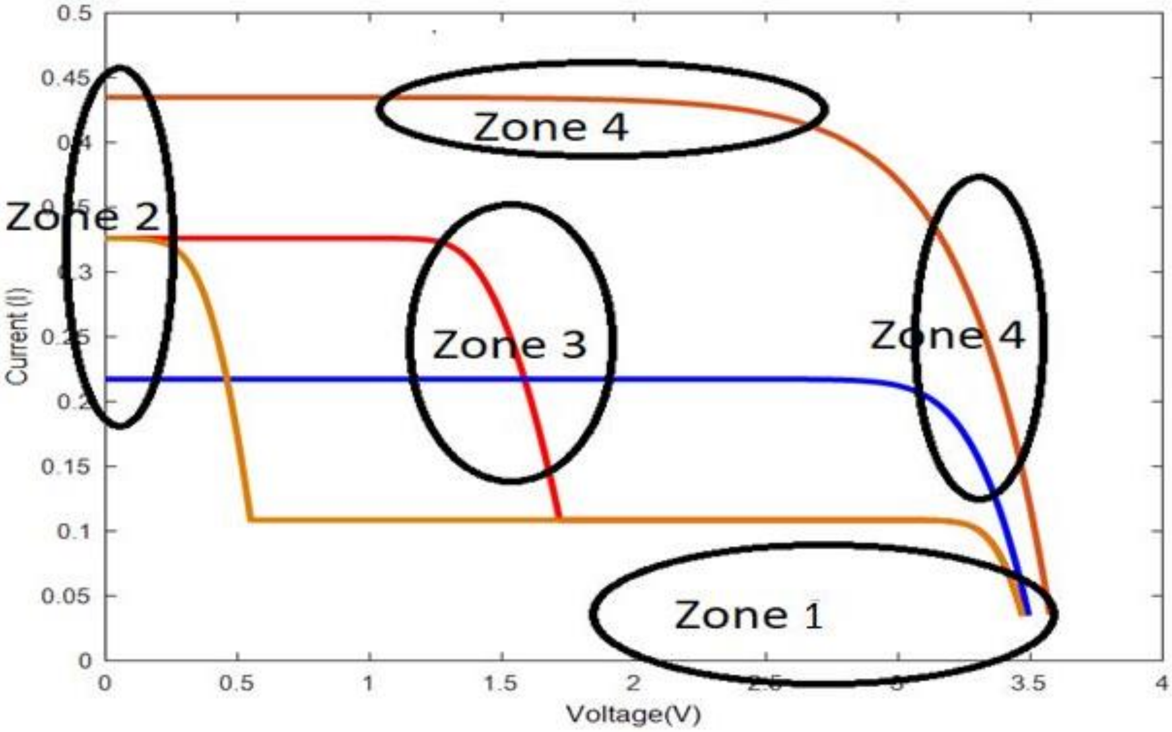


Fig. 6- 1 Characteristics IV curves of PV modules in different scenarios

Table 6-2 – Symptoms of the faults and its occurring zones

Symptom	Area of Characteristic IV	Symptom Name
S1		Reduction of maximum power
S2	Zone1	Reduction of the open circuit voltage
S3	Zone2	Reduction of short-circuit current
S4	Zone3	Presence of one or more inflection points
S5	Zone4	Deviation of the slope

The symptom "**S1**" is the first symptom that can be identified from the comparison because it is obvious that any fault will lead to a loss of the power produced. The main difference is the magnitude of power loss. On the other hand, this observation is not always true because certain faults do not lead to any loss of power e.g. disconnection of bypass diode.

The symptom "**S2**" is the difference between the open circuit voltage of the PV system in normal operation condition and the faulty condition. This symptom helps to figure out the problem with the open circuit voltage faults. In the following part, the types of faults associated with open circuit voltage has been described.

The symptom "**S3**" is the difference between the short circuit current of the PV system in normal operating condition and faulty condition. This symptom helps to identify the problem with the short circuit current faults. In the following part, the types of faults associated with open circuit voltage has been described.

The symptom "**S4**" is based on the presence of one or more inflection points. These inflection points are results from the conduction of one or more bypass diode in case of shading. Partial shading is the major cause for this kind of fault.

The symptom "**S5**" refers to deviation of the slope of IV curve at the faulty condition as compared to the normal operating condition. This deviation is caused by the parasitic resistance appeared in the solar cell and other external wire resistances.

6.3. Evolution of symptoms as the function of the severity of faults

Symptoms are generated by comparing the IV characteristics of a PV system in normal operating condition with the faulty condition. Some examples are presented here.

6.3.1. Evolution of symptom as a function of the severity of faults

The IV characteristic of a faulty PV system will change with severity of the faults. The evolution of the symptom depends upon the magnitude of fault and the number of the components in the faults condition as shown in fig. 6-2 to 6-4.

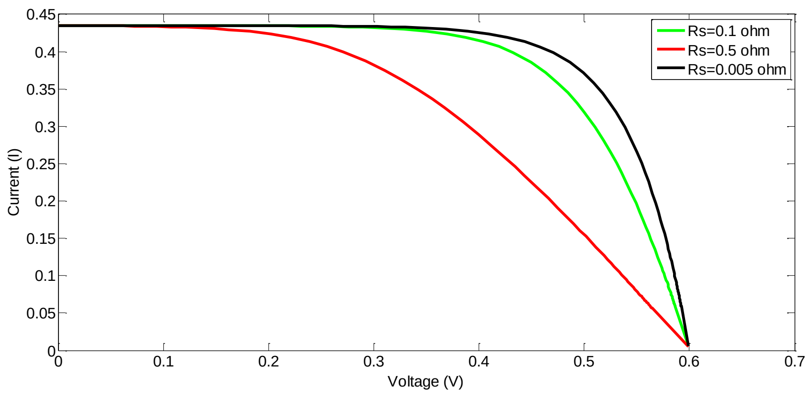


Fig. 6- 2 Effect of resistance

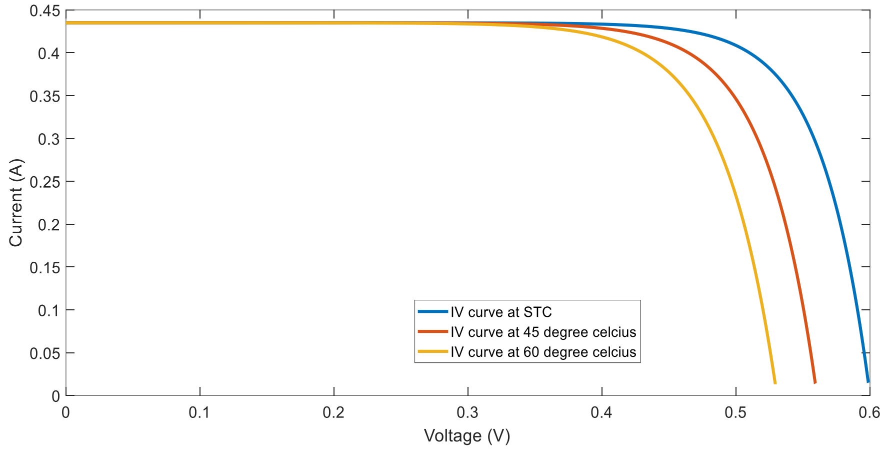


Fig. 6- 3 Effect of temperature

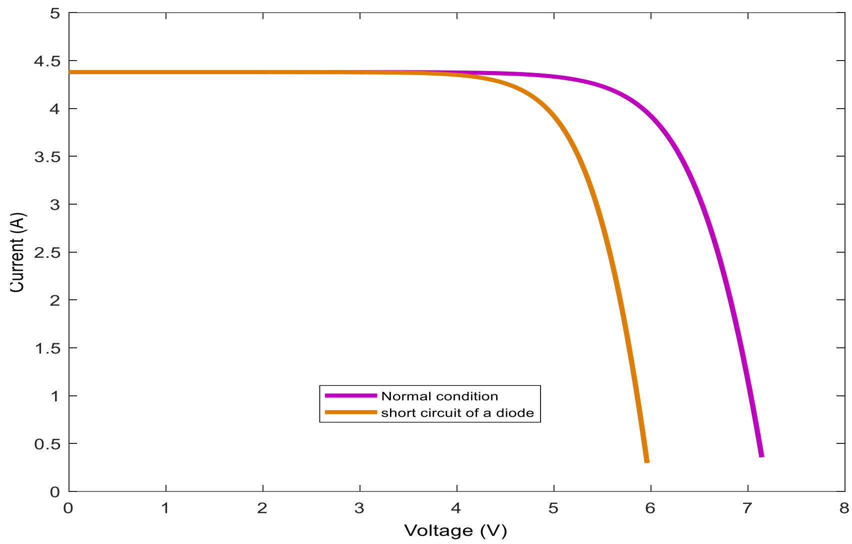


Fig. 6- 4 Short circuit of bypass diode

6.3.2. Evolution of symptom as a function of the operating condition

The fig. 6-5 shows the influence of the irradiance in the IV curve of the PV cell. Irradiance primarily affects the short-circuit current of the solar cell. The relation between the short circuit current and the irradiance is given by equation (6-1).

$$Isc=G/Gr*Isc\_r \tag{6-1}$$

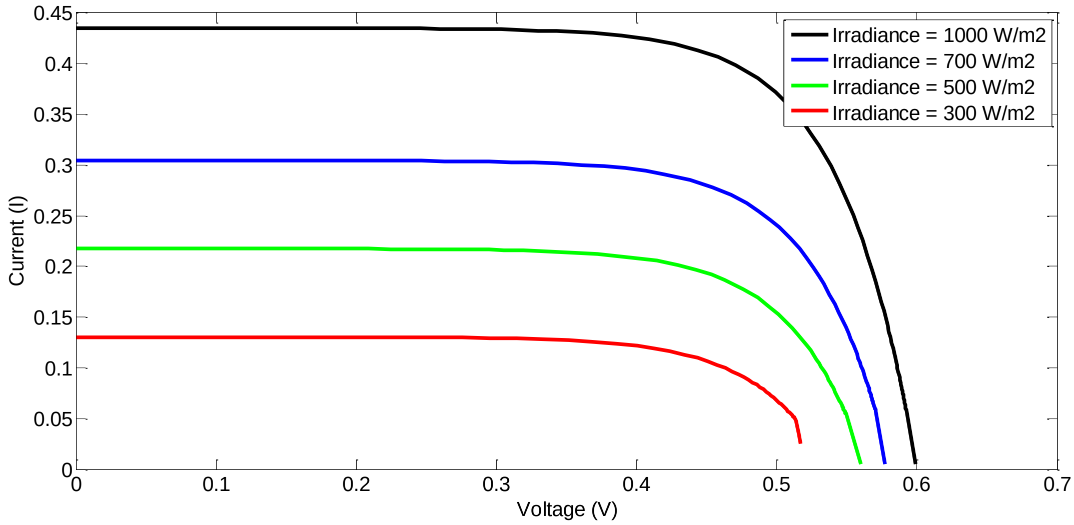


Fig. 6- 5 Influence of irradiance in the IV curve of PV cell

6.3.3. Evolution of symptom as a function of the level of system

Figures 6-6 and 6-7 show the behaviour of two different defects for the two types of system considered. Each of these two faults appears at the level of a module. Severity of these two defects is kept constant and the evolution of the symptoms is observed during of the transition from one configuration to another (module to string).

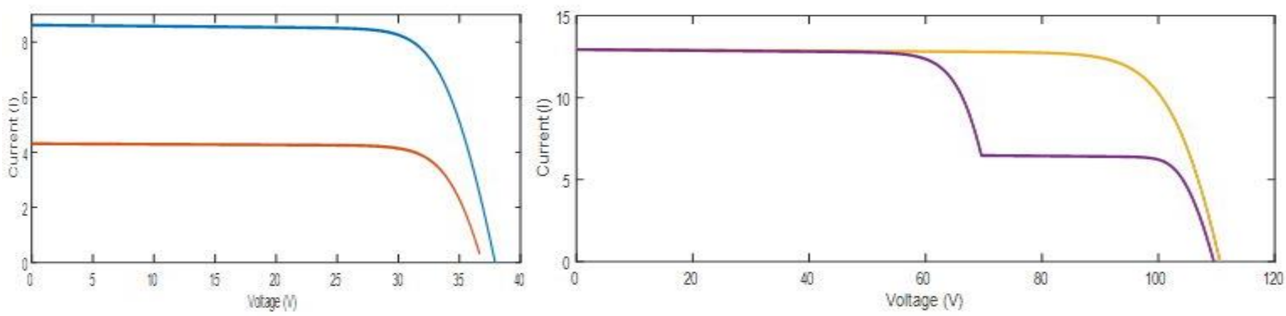


Fig. 6- 6 Fault in module and transformed to string

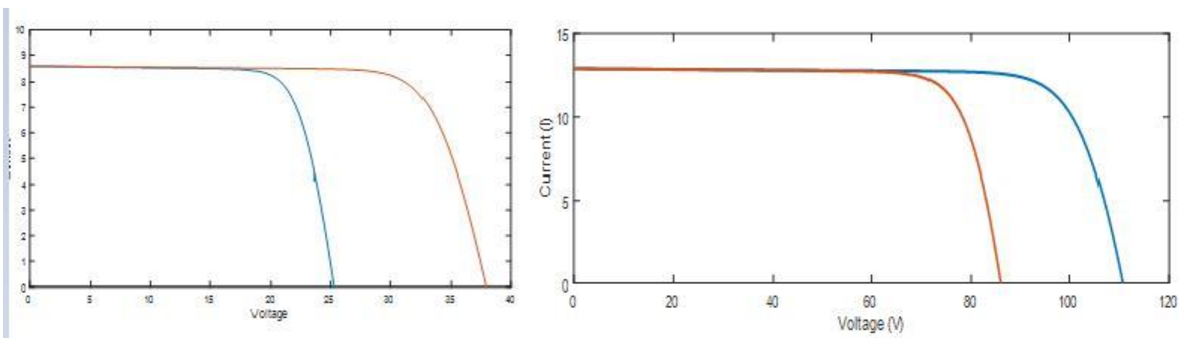


Fig. 6- 7 Fault in module and transferred to string

Two remarks can be drawn from these figures. The first observation can be made during the passage from the "module" to the "string". The reduction in the short-circuit current which appears in the "module" configuration is transformed into an inflection point in the configuration "String". While the reduction of the open circuit voltage remains unchanged of this passage. The second remark is then formulated when the "string". During this passage, the current reduction is conserved. While the reduction of the open circuit voltage is converted into an inflection point.

6.4. Qualitative analysis of detection and localization capacity of defects

The evolution of symptoms for the various faults condition is described above. Now it is required the qualitative analysis of the potential fault. Different faults have different influence in the IV characteristic of the PV system. It is required to find the peculiar characteristics for each fault which is the signature of that fault.

6.4.1. Fault signatures table for a module

Table 6-3 below presents, there are six fault signatures characteristics that can be detected. The fault bypass diode disconnection shows similar characteristics as normal condition, no changes in each IV characteristics. The faults inverse of bypass diode, shading and increase in temperature have similar kind of symptoms, loss in power and reduction in the open circuit voltage whereas the module short circuit and module inverse connection have similar symptoms as the previous group of faults but have one more symptom which is reduction in short circuit current. Partial shading has different type of symptom than others, it shows the more point of inflection. The presence of series and shunt resistance presents the deviation in the slope of the IV characteristics. The bypass diode failure and shun of the module presents the similar kind of the symptoms, reduction in the open circuit voltage and change in deviation of slope.

Table 6-3 – Module faults

S no	Nature of fault	S1	S2	S3	S4	S5
1	Normal condition	0	0	0	0	0
2	Bypass diode disconnection	0	0	0	0	0
3	Bypass diode short circuit	1	1	0	0	0
4	Inverse of bypass diode	1	1	0	0	0
5	Shading	1	1	0	0	0
6	Increase temperature	1	1	0	0	0
7	Module short circuit	1	1	1	0	0
8	Module inverse connection	1	1	1	0	0
9	Partial shading	1	1	0	1	0
10	Shunt resistance	1	0	0	0	1
11	Series Resistance	1	0	0	0	1
12	Bypass diode failure	1	1	0	0	1
13	Shunt module	1	1	0	0	1

6.4.2. *Fault signatures table for a string*

The following table 6-4 shows the signature characteristics for a string. The concept of construction of the table is same as it is done for module. The faults (connection fault) are introduced in this case.

Table 6-4 – String faults

Nature of fault	S1	S2	S3	S4	S5
Normal condition	0	0	0	0	0
Bypass diode disconnection	0	0	0	0	0
Bypass diode short circuit	1	1	0	0	0
Inverse of bypass diode	1	1	0	0	0
Shading	1	1	0	0	0
Increase temperature	1	1	0	0	0
Module short circuit	1	1	1	0	0
Module inverse connection	1	1	1	0	0
Partial shading	1	1	0	1	0
Shunt resistance	1	0	0	0	1
Series Resistance	1	0	0	0	1
Bypass diode failure	1	1	0	0	1
Shunt module	1	1	0	0	1

The qualitative analysis of the faults detection is required for the determining the fault and its location. The characteristics of each fault remains the same when the fault is at module or at the string. The symptom “S1” appears for all the defects so this symptom doesn’t contribute to identify the fault. Therefore, it is necessary to exclude this symptom and examine the symptom “S2 to S5”. When these symptoms were identified, the signature table is constructed for the diagnosis of the faults. This analysis is done with the comparison of the healthy and faulted P-V system.

6.4.3. *Flow chart*

The flow chart for the above algorithm is shown in the fig. 6-8. The flow chart has two starting process as there are two different scenarios. First flow chart follows the storing of all non-normal operating conditions associated with PV system, it follows the storing of different symptoms while another measure the physical parameters that has influence the PV system in real time. After storing of all the non-normal conditions, it is used to compare with the real-time data. The comparison of the data acquired in real time by microcontroller gives the fault that occurred.

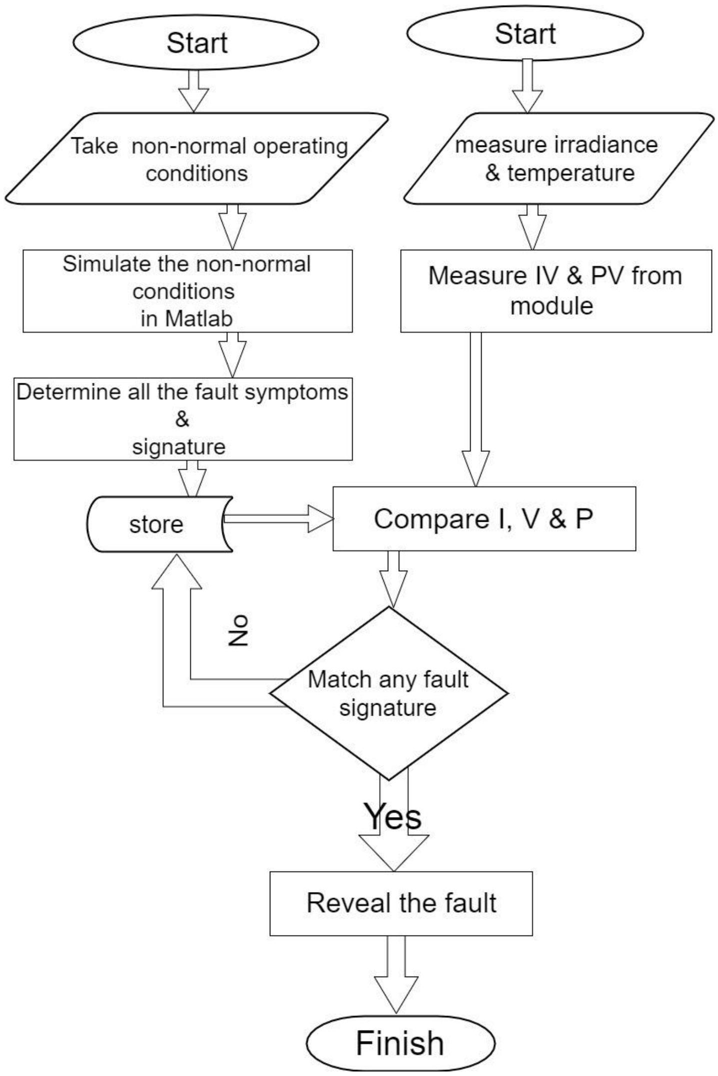


Fig. 6- 8 Flow chart

7. CASE STUDY OF NEPAL

Nepal is a developing country lies between two big countries China and India. Nepal is a country with natural as well as cultural diversities, Since Nepal is a developing country so demand for energy is increasing. Nepal is said to be one of the richest countries in the world for the water resource but unfortunately there no proper utilization of it. Despite the huge potential of hydropower, Nepal is suffering from energy deficient. The main reason for the not constructing the hydropower in Nepal is due to its huge capital investment for the construction of hydropower, in this scenario Nepal government is focusing on the low-budgeted renewable energy sources. The government of Nepal identified the solar energy can be alternative for increasing energy demand. To promote the renewable energy the government of Nepal established an "Alternative Energy Promotion Centre" AEPC. Now AEPC promotes the solar energy sector in Nepal [33]. Nepal is blessed with a solar resource as it lies at 30◦ Northern latitude which is an ideal condition. Nevertheless, Nepal experiences the five seasons there are over 300 days of sunshine annually, therefore there is always a potential for solar energy due to this reason government of Nepal is focusing on the development of the solar energy sector.

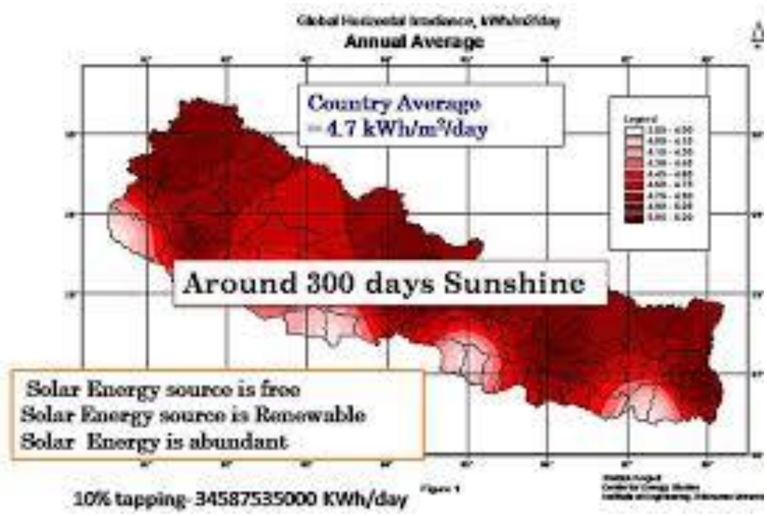


Fig. 7- 1 Solar energy potential of Nepal [34]

7.1. Current situation and opportunity of PV technology

Currently, only 76% [35] of total Nepal population has connected to the national grid and rest of the population still relies on traditional sources of power. Even in the electrified areas, there has been a power shortage. In this scenario, the government of Nepal is searching for the alternative source of energy. In this context, solar power has emerged as one of the best solutions since it is environment-friendly and consumes less time to implement. Currently, the government of Nepal is not focusing on the grid-connected solar power, but they are focusing on the isolated system so that people of remote places can have the access to lighting than other works. In this context, the government of Nepal has been actively promoting the utilization of solar PV energy. The government of Nepal has been presenting their plans and policies to address the utilization of solar energy. In Nepal, along with the AEPC other INGOs, NGOs collects the fund from different donor [36] and gives subsidies to the public for installation of the PV system [36]. Previously the subsidies were only given to the public of remote areas but now the policies have changed and now the subsidies are also given to the public of urban areas. The way that government agencies are giving the subsidies are the optimistic part for the promotion of clean energy, but also this is the fact that to make the balance between energy demand and supply government is promoting this kind of policies. From this scenario, we can conclude that there is huge potential for the solar PV system and Nepalese people are getting privilege from the solar technology.

7.2. Faults and Maintenance compare with global scenario

As already stated, Nepal is increasing the utilization of PV energy. There are more than hundred solar companies working in the field of PV technology [22]. The solar companies basically provide the installation facilities and some maintenance work. Generally, in Nepal, a solar company gives the guarantee/warranty for the certain period. In that period, any malfunction, the companies maintain or monitors defects. The most maintenance work done is Nepal is checking the battery conditions and checking of connections during the warranty period. After the completion of the guarantee period, the maintains of fault monitoring case is very rare. Only a few people or stakeholder are concerned about the monitoring and maintenance of faults, so we can almost say there is no maintenance of a solar PV system. So, due to this reason there no proper idea regarding the most frequent faults in Nepal. It is said that the major problem for the PV system is unaware of cleanliness of the panel and shading. Due to improper cleanliness problems, the solar panels have dust, dirt, sand, clay etc. the deposition of this kind of material not decrease the efficiency of the panel but also causes effective aging, corrosion in the metallic connection. Unlike in other countries the owner of solar panel is more careless, they are not using the solar energy inefficient ways.

There are not such systematic studies about the fault and maintenance of PV system in Nepal, but then measure problems associated with the PV panel of Nepal are recognised as following

- Shading
- Inappropriate position of panel (hit and trial method)
- Dust, dirt, soiling, poor cleanliness, careless
- Corrosion of cable, joints
- Poor connections
- No monitoring body, use it until it works after some malfunctions then only alert
- No budget for maintenance work
- Solar company are more focus on quantity than quality

7.3. Case study

The simulation work is carried out for the real site. The site is one of the villages of Nepal known as Bhorleni V.D.C Makawanpur District, where the solar PV is installed as the primary source of the electricity. The installed capacity of the solar PV system is 35 KW. The installed system can have various unfavourable environmental conditions. This part tries to simulate the effect of such unfavourable conditions in that site for one panel. The system will behave as the integration of this single panel i.e. the generalisation can be done for other panel for the whole system.

7.3.1. Case – I: The partial uniform shading

Shading is a natural process and it is inevitable. The shading effect decreases the power generation of the PV panel and it is described in the earlier part. Now it is required the quantitative analysis rather than qualitative analysis. The simulation results present the variation of voltage, current, and power in accordance with the shading problem. The figures below show the difference in the output for the two different cases i.e. in a normal case and in the cloudy day. Cloudy can be presumed as the partial uniform shading problem. The result clearly shows there is an extreme decrease in the output current as seem in fig no 7-3 whereas, the voltage as shown in fig no 7-2 it has not so The percentage change in the data parameter can be seen in fig.7.4. This kind of unfavourable condition presents the backup strategy for the reliability of the system. However, this condition can be overcome with the help of installation of the high rated power PV system high capacity batteries to store more energy, eventually, it increases the cost of the system.

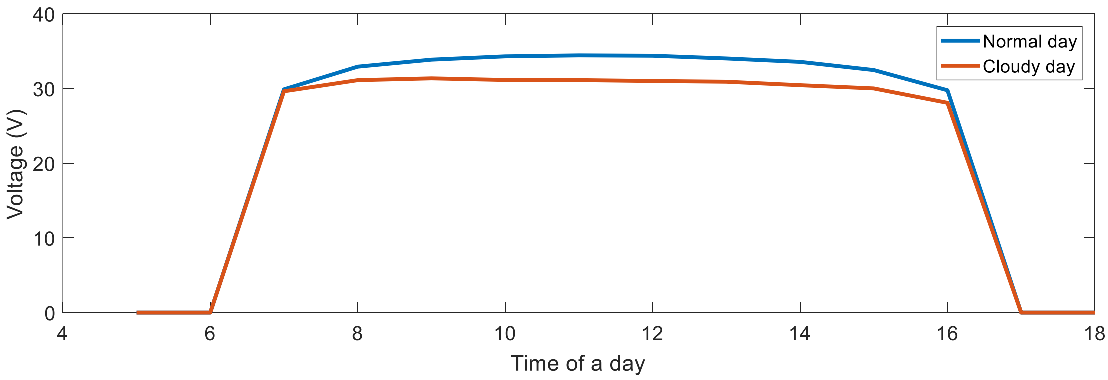


Fig. 7- 2 Generated voltage from PV module

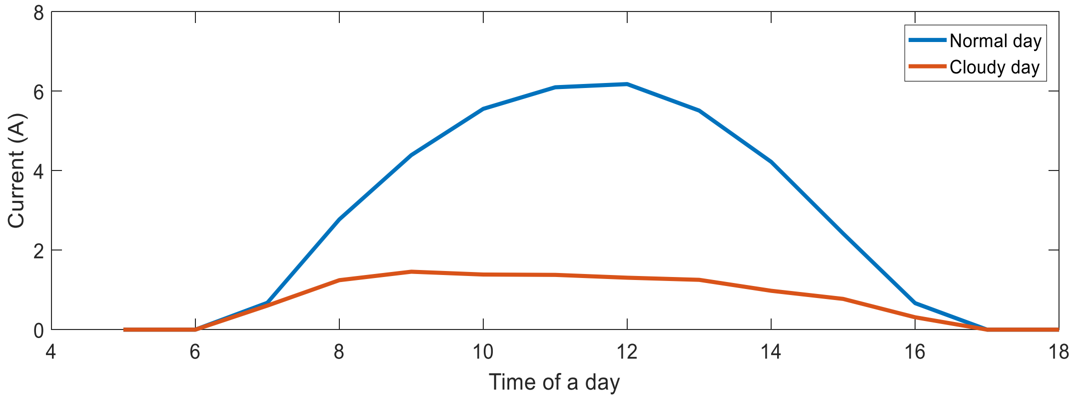


Fig. 7- 3 Generated current from PV module

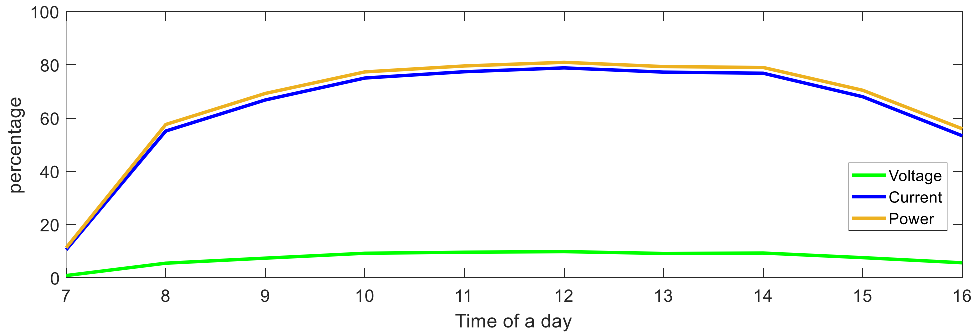


Fig. 7- 4 Percentage changes in data parameter

7.4. Case- II: Degradation of the system

As the installed system must with stand the different weather conditions. The variation in the weather condition has different effect on the PV system. The electrode oxidation and EVA and back sheet delamination are the major factor for degradation. The degradation of the solar module can be modelled with help of the increase in series resistance [13]. The following simulation is considering for the context of Nepal rural village, where there is seldom maintenance occurs so it is logical to increase significant value of resistance for the simulation work, reference taken from a example of Korea [13].

The estimated value for the increment of a series resistance due to aging and its consequences in the power generation is shown in table no 7-1. The table shows there is negligible value of series resistance in the first year of operation and the series resistance begin to increase as the aging occurs. The estimated series resistance is 0.27 Ω for the fifth year which causes almost 8% loss in a single panel, similarly for the 10 years of time the resistance increases to 1 Ω which causes 25 % loss in a panel. This shows that there is need of proper monitoring for the PV system to maintain its efficiency.

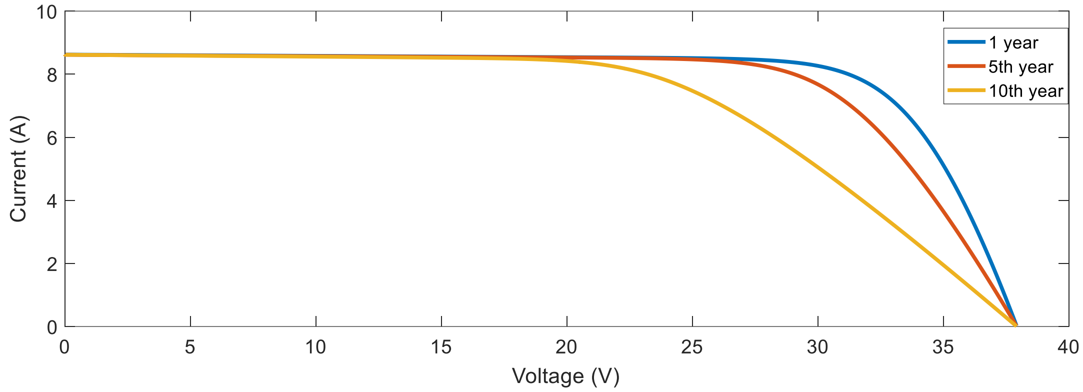


Fig. 7- 5 IV curve of PV module with degradation over a time

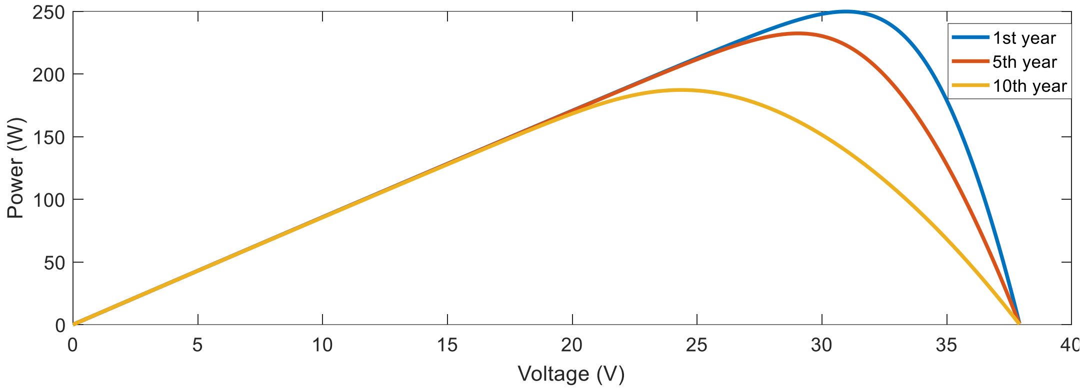


Fig. 7- 6 PV curve of a PV module with degradation over a time

Table 7-1 – *Comparison of power generation over a time with degraded PV module*

Sno	Years	Resistance	Power generated (W)	Power available (%)
1	1st	negligible	249.8356	100
2	5th	0.27Ω	232.56	92.86
3	10th	1Ω	187.245	74.95

8. CONCLUSION AND RECOMMENDATION

From this work, solar cells are studied, the parameter associated with the cells are determined from the dark IV characteristics. The non-operating conditions of PV system are studied with the variation of the physical parameter as well as the level of the PV system. The symptoms and operating zone of different faults are defined. The algorithm for determining the kind of faults and level of fault is presented. The experimental, as well as simulation, is carried out from the different kind of faults. The different kind of faults associated with a solar cell are the presence of the series resistance, mismatch effects, these are the faults mostly depend upon the manufacturing process. The fault with the module of PV cell are the faults associated with bypass diode, its inability to behave as required, partial shading, degrading, aging, hotspots etc. The faults associated with the string of a PV are the mismatches of the PV modules, it may temporary or permanent mismatch. The temporary mismatch is the result of the partial shading, an uneven temperature of the modules, whereas the permanent mismatch is the cause of the aging degradation, hotspot creation etc. These all faults are simulated and observed the IV and PV characteristics. These simulated results are the references for the detection of the faults.

As stated earlier, there is no proper data for the analysis of faults and non-operating conditions of Nepal, so it is not exacta data for the simulation work. The parameters for the simulation work is assumed as per the global context so there may be some error. This case study tries to give some glimpse of the PV system on Nepal. The installed PV power system are also not in regular suppression and maintenance. The case study shows there is almost 8% power loss for five years of time and almost 25 % for 10 years of time. This suggests that the owner of a solar power system of Nepal is careless and they aren’t properly utilising the solar PV power. They are decreasing the efficiency of solar panels rapidly than other global nations. This thesis work suggests that proper information should be given to the public for the optimum utilization of PV system throughout their expected life of the panel. Proper cleanliness as well as the fault monitoring system should be included. This is only how there will be proper utilisation power as well as they will be more benefited from the PV system.

9. FUTURE WORK

The simulation work to carried out in the Matlab for all the non-operating condition is not possible. The modelling in the simulation works sometimes do not work as in the practical field. Though Matlab provides much flexible for modelling it is not sufficient to model and simulate all the faults associated with PV panel. However, in the future, the modelling of each fault which is unable to simulate can be a model with great precision. In this thesis, only the theoretical simulation is carried out, the validity of simulation work should be performed in the practical field, this provides the future work. After only the practical experiments this work will be a reference to the others, so it is important to execute the experimental setup to validate this work.

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10. Appendix I

Electrical Characteristics

STC	STP225-20/Wd
Optimum Operating Voltage (Vmp)	29.6 V
Optimum Operating Current (Imp)	7.61 A
Open - Circuit Voltage (Voc)	36.7 V
Short - Circuit Current (Isc)	8.15 A
Maximum Power at STC (Pmax)	225 W
Module Efficiency	13.6%
Operating Module Temperature	-40 °C to +85 °C
Maximum System Voltage	1000 V DC (IEC) / 600 V DC (UL)
Maximum Series Fuse Rating	20 A
Power Tolerance	0/+5 %

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5;
Power measurement tolerance: ± 3%

NOCT	STP225-20/Wd
Maximum Power (W)	165 W
Maximum Power Voltage (V)	26.9 V
Maximum Power Current (A)	6.12 A
Open Circuit Voltage (Voc)	33.8 V
Short Circuit Current (Isc)	6.65 A

NOCT: Irradiance 800 W/m², ambient temperature 20 °C, wind speed 1 m/s;
Power measurement tolerance: ± 3%