2. PHOTO VOLTAIC THEORY

2.1 OVERVIEW

This chapter briefly describes the theory behind the photo voltaic power generation and its simple equations. Number of theories involved in the PV modules, namely Quantum Physics, Semi-Conductor Physics and Electrical Circuit Theories etc. Each theory itself can be described through voluminous books. For ease of understanding, section 2.2 defines the photoelectric effect with semiconductor materials. Further, section 2.3 defines the Solar Cell and its essential properties and section 2.4 explains the partial shading and hotspot phenomena in a PV module. Excerpts of the ASTM 2481-08 standard for the hotspot testing are defined in section 2.5.

2.2 PHOTOELECTRIC EFFECT

Light strikes at a metallic surface, emits electrons which is defined as (S.Krane). The emitted electrons are called photo electrons. Emitted electrons are having complex spectrum of energies which can also reveal details about the structure of the target material.

Subsequently, the relationship between light, photons and electrons are defined by Albert Einstein - the light generated photon energy is related with an electromagnetic wave frequency v is

$E = hv$--- *Eqn. 2. 1*

Where h is the Planck’s constant.

Also the light generated photon energy is related to wavelength of the electromagnetic wave, wherein $v = c/\lambda$ which gives

$E = hc/\lambda$--*Eqn. 2. 2*

Here, Photons are the concentrated bundles of particles which have linear momentum and energy. Also photons travel with electromagnetic waves at the speed of light hence obeying the relativistic relationship (S.Krane). Combining with Eqn. 2.2 above, the momentum p

$p = h/\lambda$ ---*Eqn. 2. 3*

When a single photon strikes at a material such as metallic conductor, semi-conductor etc., the entire energy is instantly transferred to a single photoelectron. In case the photon energy hv is more than that of the work function **Φ** (S.Krane).

This quantum theory is well demonstrated through semiconducting materials such as Silicon (Si) which is a Group IV element. In semiconductor physics, the energy levels of an electron has well defined bands. The valance band energy E_v, is defined as the energies of valence orbital which forms a bond between (Markvart, 2000). Conduction band energy E_c is the next higher level band which is separated from the valance band by the band gap or energy gap. The gap between the two energy bands E_g in eV is defined as which is an important property of a semiconducting material for Solar Cell application.

$E_g = E_c - E_v$---*Eqn. 2. 4*

When the incident photon energy as defined in Eqn.2.2 is more than the E_g defined in Eqn.2.4, then a photo electron is generated.

Majority of PV modules are made of compounds of semi-conducting materials from Group IV (Silicon and Germanium) and alternatively Group-III /V and Group-II /VI. These materials are in mono crystalline, multi crystalline and in amorphous structure.

Table 2.1 below indicates the Energy gaps E_g of the principal semiconductors (Markvart, 2000).

Table2.1 Energy gaps of Principal Semiconductors

Material	Energy Gap eV	Type of Gap
Crystalline Si	1.12	Indirect
Amorphous Si	~1.75	Direct
$CuInSe_2$	1.05	Direct
CaTe	1.45	Direct
GaAs	1.42	Direct
InP	1.34	Direct

2.3 SOLAR CELL

The solar cell converts sunlight into electricity directly by photoelectric effect. Figure 2.1 shows the typical structure of a silicon solar cell in use, in the market. The finger contact in the front and rear of the cell reap the generated current through the incident light on the surface of the solar cell.

Top surface is covered with a thin layer of dielectric material the antireflection coating or ARC, to limit the reflecting light energy from the top surface of the cell.

Figure 2.2 shows the semiconductor energy band diagram which is under illumination. Incident light generates electron-hole pairs at the junction in an n- (Markvart, 2000). Excited cell generates electrons from base and holes from the emitter, then diffuses at the p-n junction and gets swept away by the electric field, thus producing the electric field. The p-n junction which separates opposite charges and generates the I_l current between the bands.

$$I = I_l - I_o\left[exp\left(\frac{qV}{kT}\right) - 1\right] \text{---}\mathit{Eqn.\ 2.\ 5}$$

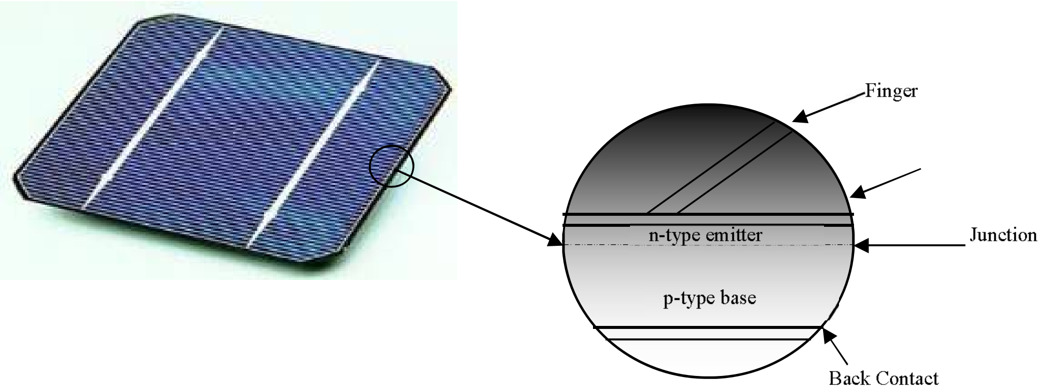

Figure 2.1 *Typical Silicon Solar Cell*

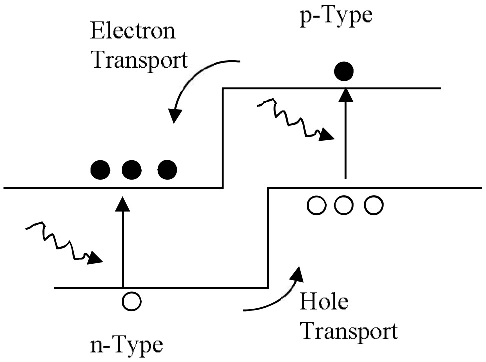

Figure 2.2 Schematic representation of currents in a p-n junction under illumination

The Current-Voltage (*I-V*) characteristics of a solar cell explain how the incident light is getting generated as current and voltage and its electrical equilibrium states. Figure. 2.3 below shows the electrical diagram of the PV cell wherein the cell current I, voltage across V, incident light current I_l, photo diode current I_D, current across shunt (load) I_{sh} with the series resistance within cell R_s and shunt resistance R_{sh} are all indicated.

The current generated by the solar cell is expressed in Eqn. 2.1 below, wherein the generation of current *I* from the incident light *I_l* is expressed as the parallel current across the p-n junction of the photo diode. The output current is equal to the difference of the light generated current and the diode current *I_D*.

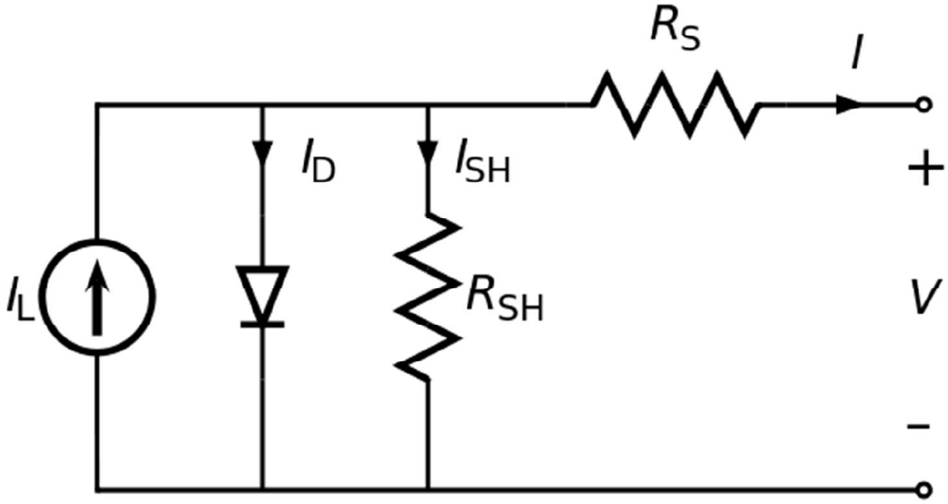

Figure 2.3 Equivalence circuit of PV Cell

The I-V characteristics give two important points: One as short circuit current I_{sc} and open circuit voltage V_{oc}. When the current I = 0, all the light generated current pass through the diode as the circuit is open circuited and when V=0, it is short circuited. The open circuited voltage V_{oc} can be expressed as below Eqn. 2.2

$$Voc = \frac{kT}{q} ln\left[\frac{I_L}{I_o} + 1\right] \text{--} \textit{Eqn. 2. 6}$$

The key point to note here is that both current I_l and Io depend on the structure of the device, although the value of I_o can vary by many orders of magnitude depending on the device geometry and manufacturing technology which determines the V_{oc} of the devices.

Additionally, open circuit voltage (V_{oc}) of the PV cell depends of its band gap of material, dark saturation current, light generated current and the temperature of cell.

There is no power produced, when the circuit is open or short. The maximum power produced P_{max} is a device at the peak of I_m and V_m which is known as maximum power point (MPP). The I_m and V_m are theoretical peak of a device but in practical terms I_{sc} and V_{oc} are realistic in a device and the gap is defined as the fill factor (FF), this is expressed by Eqn. 2.3

$$P_{max} = V_m \times I_m = FF\times\ V_{oc} \times I_{sc} \text{-------------------------------} \textit{Eqn. 2. 7}$$

The efficiency η of a solar cell is defined as the division between MPP P_{max} produced by the cell at the maximum power point under standard test conditions with power of the incident light upon it. The standard test condition is defined as irradiance at 100 mW/cm^2 , standard reference AM1.5 spectrum and temperature 25°C.

2.4 PARTIAL SHADE BEHAVIOUR AND HOT-SPOT PHENOMENA

In practical applications, many factors affect the performance of the PV modules. Airborne dust materials are very common in tropical regions such as Indian Sub-Continent. Also during climatic changes and wind directions there

(Vivek K, 2015).

Especially, the study on effect of particle shading due to dust particles has been of great interest as the tropical regions such as the Indian subcontinent, the Middle-East, Saharan Africa and the south-western United States and Southeast

(Abhishek Rao., 2014).

(Deline C. A., 2013)

(Shading and bypass diode impacts to energy extraction of PV arrays under

(Ishaque, 2011) (Pieter, 2014) on the effect on partial dust shading on the solar system were reported in the literature. Particularly, dust accumulation over the surface of PV modules creates significant impact such as (a) reducing the energy input to the cell; (b) increasing energy losses in the shaded cells, and (c) reverse bias in the cell due to reduced illumination. The PV cell without shading is forward biased during the sunny day time and the electrical output of the same is characterized by I-V and P-V curves. On the other hand, when the solar PV cell is under shadow conditions, the reverse bias occurs and it prevents excitation of a PV cell that can be verified through dark characteristics.

The partial shade over the surface of a PV cell is classified as high shunt or low (BS 61215, 2005). The PV cell is referred as 'voltage limited' (Type-A) with high shunt resistance when the small area of the cell is shaded causing reverse performance, while the same is referred as 'current-limited' (Type-B) with low shunt resistance when the large area of the cell is shaded leaves only small area for exposure to illumination. In later, the current mismatch between adjacent cells causes the reverse performance. Theoretically, Type-A shade has slow and uniform temperature rise over the large un-shaded portion of the cell thereby has limited chance of damaging the cell. On the other hand, Type-B shade has rapid temperature rise over small area of un-shaded portion causing hot-spots and damage to the cell. The commercial PV modules are included with bypass (Murtaza, 2014) (Zheng, 2014).

Due to the partial shading, hot-spots generated on the photovoltaic cell surface

(Stefan Wendlandt, 2010) such as cell properties, leakage of current during shade, type of shade and opacity of the shade, wind velocity, weather (Govindasamy (Mani) TamizhMani, 2008). The hot-spot heating can occur due to shading by dust deposition, trees or building shades, passing clouds, strict opaque object and atmosphere fluctuation.

Localized hot spot heating occurs in a PV cell, which is caused by faulty (E. Molenbroek, 1991) partial shading / irradiation level during fault / material imperfection / fabrication flaws / damages etc. When the faulty PV module / cell operating current exceeds the reduced short circuit current (I_{sc}), it shall not produce energy, rather starts to consume power from the other PV cells connected in series. Due to the above phenomena, localized heating is expected to occur, where the surface temperature could rise above 200°C. Higher V_{oc} cell develops more power dissipation across the faulty PV cell causing more temperature rise than lower V_{oc} cell.

Built-in bypass diodes are provided in PV modules to prevent localized hotspots. However, there are characteristics mismatches between the diode and the module which does not prevent hotspots for all faulty cases. Commercial PV modules are provided with a bypass diode for every eighteen to twenty PV cells.

Figure 2.5 shows a typical PV module with bypass diode arrangement. However, due to the mismatch in characteristics between the PV cells and a by-pass diode, the prevention of hot-spot is not ensured in totality, especially in the event of diode failure. The effect of shaded PV module on power output of typical PV installations is a nonlinear function in which a small amount of shade (Deline C. , 2009).

When a single cell in a string on a PV module gets shaded, the whole string output is lost and also the bypass diode is switched on to prevent the module heating. The energy output from the PV module would become zero when two cells are shaded in a 36 cell module with two strings of 18 cells each; this results in drastic reduction in the performance of the array. PV cell area shade percentage plays a vital role in energy reduction levels and decides the bypass diodes activation. The spatial extent of shade percentage and the output (Deline C. , 2009).

Accordingly the shade impact program is defined with variable cell shade percentage and change in shade media, in order to thoroughly understand the shade impact on the power output. The focus on both energy loss and the hot-spot creation due to partial shading of the solar panel and its level of temperature rise is an issue that is complex and difficult to predict.

2.5 HOT-SPOT TESTING STANDARDS AND PROCEDURES

Experimental approach to test the hot spot phenomena of a PV module can consider multiple variables and scenarios such as:

- PV Module Materials Mono Crystalline Si and Poly Crystalline Si PV modules
- Module Current & Voltage Level (viz. 12V @ 5A / 24V@ 10A & 48V / 12A)
- Irradiation level
- Type of shading / shadowing
- Location of Fault / Shading in the module

It is not practically possible to create optimal faulty conditions and hence worst case possibilities shall be the testing criteria. Hot spot creation and temperature measurement by intrusive methods and non-intrusive methods defined in ANSI (UL-1703, 2004) IEC 61215 (BS 61215, 2005) IEC 61646 (EN, 2008) (ASTM-E-2481, 2008).

Hot Spot Test Procedure ASTM 2481-08 is used for this research. This test method provides a procedure to determine the ability of a photovoltaic (PV) module to endure the long-term effects of periodic "hot spot" heating associated with common fault conditions such as severely cracked or mismatched cells, single-point open circuit failures (for example, interconnect failures), partial (or non-uniform) shadowing or soiling. Such effects typically include solder melting or deterioration of the encapsulation, but in severe cases could progress to combustion of the PV module and surrounding materials.

There are two ways in which cells can cause a hot spot problem; either by having a high resistance so that there is a large resistance in the circuit, or by having a low resistance area (shunt) such that there is a high-current flow in a localized region. This test method selects cells of both types to be stressed.

This test method does not establish pass or fail levels. The determination of acceptable or unacceptable results is beyond the scope of this test method.

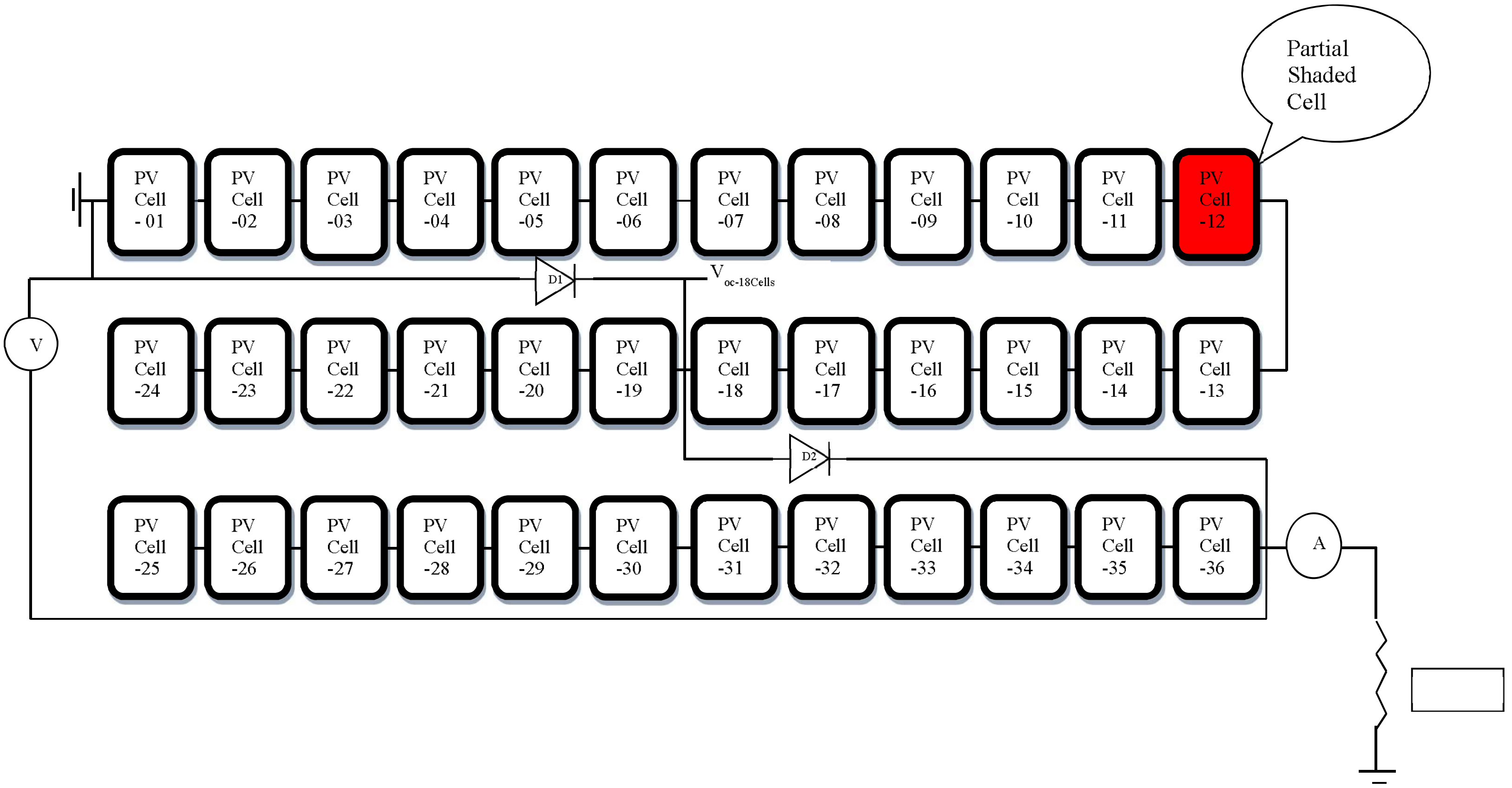

Figure 2.4 Typical configuration of commercial PV Module

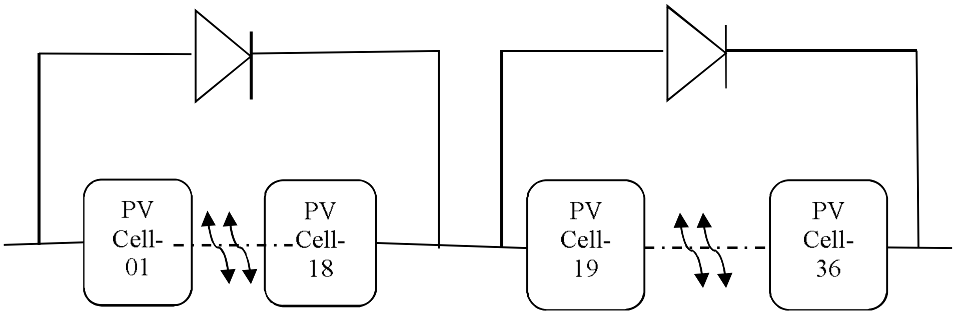

Figure 2.5 Typical Bypass diode configuration PV Module

2.5.1 Hot Spot in Application Perspective

The design of a photovoltaic module or system intended to provide safe conversion of the sun's radiant energy into useful electricity must take into consideration the possibility of partial shadowing of the module(s) during the operation. This test method describes a procedure for verifying that the design and construction of the module provides adequate protection against the potential harmful effects of hot spots during normal installation and use.

This test method also describes a procedure for determining the ability of the module to provide protection from internal defects which could cause loss of electrical insulation or combustion hazards.

Hot-spot heating occurs in a module when its operating current exceeds the reduced short-circuit current (I_{sc}) of a shadowed or faulty cell or group of cells. When such a condition occurs, the affected cell or group of cells is forced into reverse bias and dissipates power, which can cause overheating.

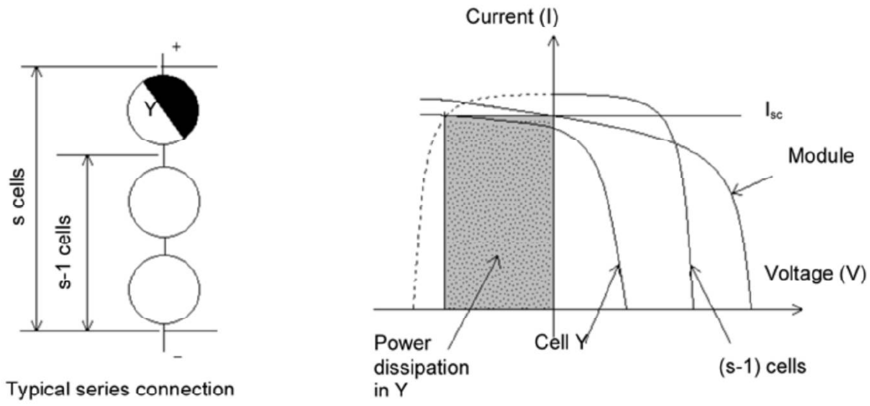

Figure 2.6 Hot Spot Effect

NOTE—the correct use of bypass diodes can prevent hot spot damages from occurring.

Figure.2.6 illustrates the hot-spot effect in a module of a series string of cells, one of which, cell Y, is partially shadowed. The amount of electrical power dissipated in Y is equal to the produce of the module current and the reverse voltage developed across Y. For any irradiance level, when the reverse voltage across Y is equal to the voltage generated by the remaining (s-1) cells in the module, power dissipation is at a maximum, when the module is short-circuited. This is shown in Figure. 2.6 by the shaded rectangle constructed at the intersection of the reverse I-V characteristic of Y with the image of the forward I-V characteristic of the (s-1) cells.

By-pass diodes, if present, as shown in Figure.2.7, begin conducting when a series-connected string in a module is in reverse bias, thereby limiting the power dissipation in the reduced-output cell.

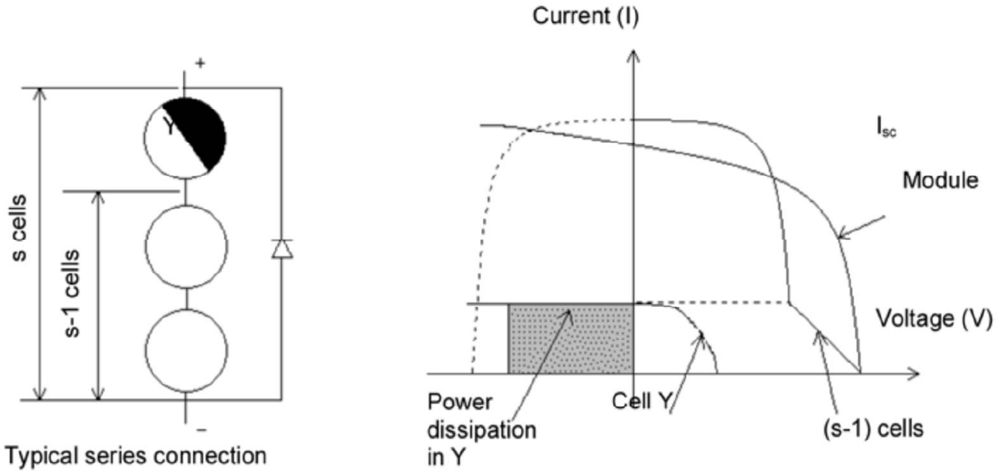

Figure 2.7 Bypass Diode Effect

The reverse characteristics of solar cells can vary considerably. Cells can have either high shunt resistance where the reverse performance is voltage-limited or have low shunt resistance where the reverse performance is current-limited. Each of these types of cells can suffer hot spot problems, but in different ways.

2.5.2 Low-Shunt Resistance Cells

The worst case shadowing conditions occur when the whole cell (or a large fraction) is shadowed. Often low shunt resistance cells fall in this category because of localized shunts. In this case, hot spot heating occurs because a large amount of current flows in a small area. Because this is a localized phenomenon, there is a great deal of scatter in performance of this type of cell.

Cells with the lowest shunt resistance have a high likelihood of operating at excessively high temperatures when reverse biased. Because the heating is localized, hot spot failures of low shunt resistance cells occur quickly.

2.5.3 High Shunt Resistance Cells

The worst case shadowing conditions occur when a small fraction of the cell is shadowed.

High shunt resistance cells limit the reverse current flow of the circuit and therefore heat up. The cell with the highest shunt resistance will have the highest power dissipation.

Because the heating is uniform over the whole area of the cell, it can take a long time for the cell to heat up to the point of causing damage.

High shunt resistance cells define the need for bypass diodes in the module's circuit, and their performance characteristics determine the number of cells that can be protected by each diode.

The major technical issue is how to identify the highest and lowest shunt resistance cells and then how to determine the worst case shadowing for those cells. If the bypass diodes are removable, cells with localized shunts can be identified by reverse biasing the cell string and using an IR camera to observe the hot spots. If the module circuit is accessible, the current flow through a shadowed cell can be monitored directly.

However, many PV modules do not have removable diodes or accessible electric circuits. Therefore a non-intrusive method is needed that can be utilized on those modules.

The selected approach is based on taking a set of I-V curves for a module with each cell shadowed in turn. Figure.2.8 shows the resultant set of I-V curves for a sample module. The curve with the highest leakage current, at the point where the diode turns on, was taken when the cell with the lowest shunt resistance was shadowed. The curve with the lowest leakage current, at the point where the diode turns on, was taken when the cell with the highest shunt resistance was shadowed.

If the module to be tested has parallel strings, each string must be tested separately.

2.5.4 Procedure

Measure the electrical performance (I-V characteristics) of the module.

Expose the module to an irradiance of 800 to 1000 Wm^{-2} through natural sunlight where the module temperature must be stabilized within 65°C before beginning the measurements.

It is not necessary to correct the value to standard test conditions (STC).

After thermal stabilization is attained, determine the maximum power current IMP1 according to Test Methods.

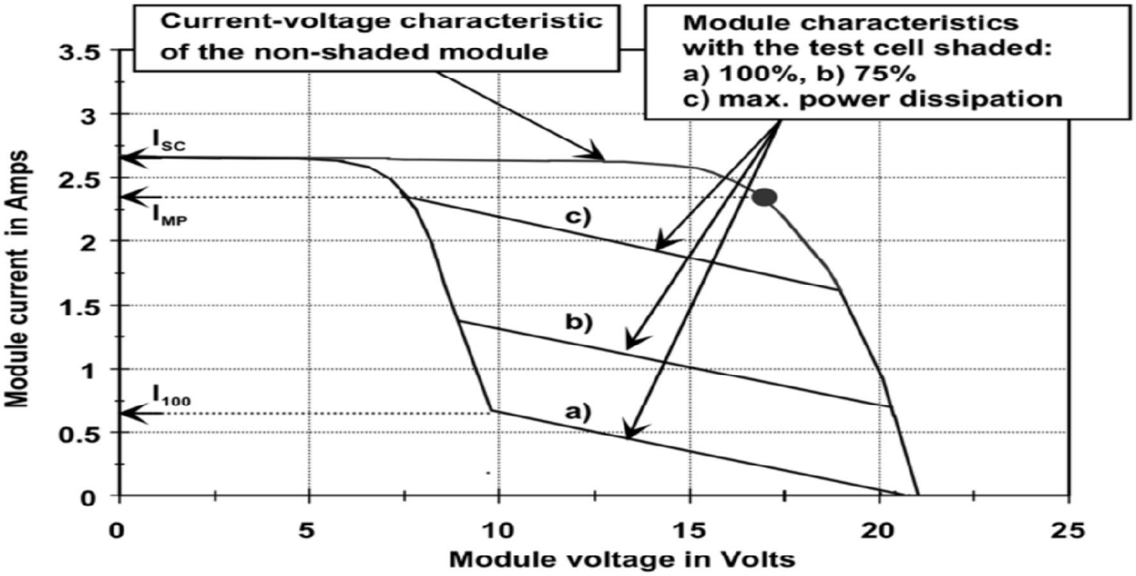

Figure 2.8 Module I-V Characteristics with Different Cells Totally Shadowed

- Completely cover each cell in turn, measure the resultant I-V curve and prepare a set of curves like Figure. 2.8.
- Select the three cells with the lowest shunt resistance (highest leakage current).
- Select the cell with the highest shunt resistance (lowest leakage current).
- NOTE —it is important to ensure that individual cells are completely covered during the I-V curve characterization procedure.

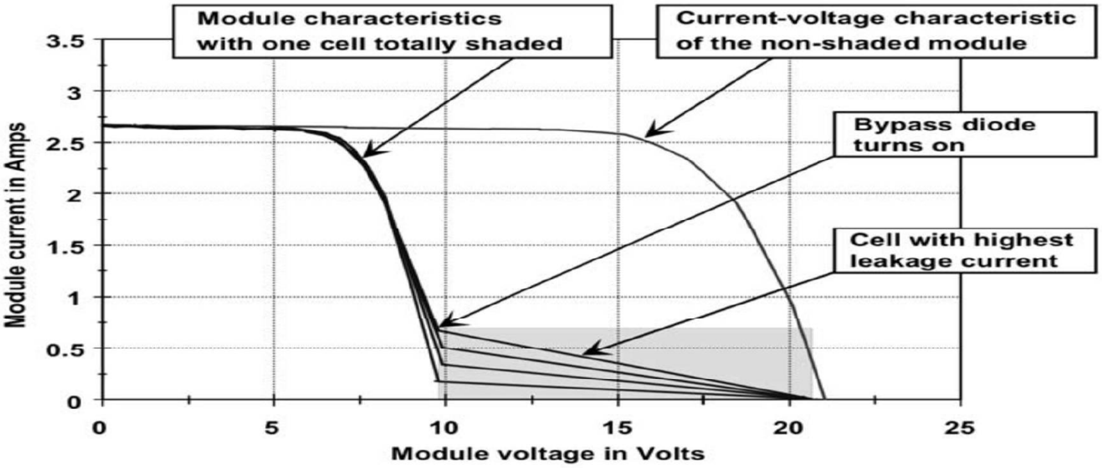

Figure 2.9 Module I-V Characteristics with the Test Cell Shadowed at Different Levels

- Leaving even 1% of a cell uncovered may cause the wrong cell to be selected for the stress testing. For each of the selected cells determine the worst case covering condition by taking a set of I-V curves with each of the test cells covered at different levels as shown in Figure. 2.8. The worst case covering condition occurs when the "kink" in the I-V curve of the shadow covered module coincides with I_{MP1}. (line "c" in Figure. 2.9)
- Select one of the three lowest shunt resistance cells selected in 5. Cover that cell for the worst case condition as determined in 6. Short-circuit the module.
- Expose the module to the illumination source. Irradiance must be between 800 and 1200Wm-2. Record the value of short circuit current ISC, irradiance, ambient temperature and module temperature.

- Maintain this condition for a total exposure time of 1 h.
- Repeat 7, 8, 9 for the other two low shunt resistance cells selected in 5.
- Cover the highest shunt resistance cell to the worst case condition as determined in 6. Short-circuit the module. Expose the module to the illumination source. Irradiance must be between 800 and 1200Wm-2. Record the value of short circuit current Isc, irradiance, ambient temperature and module temperature.

2.6 SUMMARY

Basic theories behind a PV cell are explained with the simple properties of solar cells semiconducting material, in this chapter. Further the partial shade and hot-spot phenomena are explained with definition of the role of bypass diodes. The procedure for testing the hotspot phenomena is from the ASTM 2481-08 standard. This chapter gives an overall understanding for the research design and empirical test defined in later chapters.