QUANTITATIVE STUDY ON THE SERIES RESISTANCE OF A MONOCRYSTRALLINE SILICON SOLAR CELL

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Abstract

This paper describes the device physics of silicon solar cell using basic equations of minority carriers with its boundary conditions; it also studies the series resistance of the cell in actual atmospheric conditions. Also, the effects of lead contact resistance of the measuring circuit on the I-V curve of the cell are discussed.

Introduction

Nowadays, the world's energy needs are growing steadily. However, the conventional sources of energy are limited. Solar energy such as photovoltaic energy (PV) is the most available energy sources which is capable to provide this world's energy needs. The conversion of sunlight into electricity using solar cells system is worthwhile way of producing this alternative energy. Photovoltaic system uses various materials and technologies such as crystalline silicon (c-si), cadmium telluride (cdTe), Gallium arsenide (Ga As), chalcopyrite films of copper-Indium-selenide (cuInse$_2$), etc (Shockley et al. 1952). Now, silicon solar cells represent 40% of the world solar solar cells production and yield efficiencies well higher than 25% (Wang et al 1990). In solar technology, the main challenge of researchers is to improve solar cells efficiency. Some studies have previously been reported on the performance of a monocrystalline silicon solar cell of diameter-100mm (manufactured by BP solar systems limited, England) in the sokoto environment (Atiku et al 1985) Akiku, et al (1985), Table 1 gives the values of open-circuit voltage (V$_{oc}$), short-circuit current (Isc), maximum-power voltage (Vmp), maximum-power current (Imp), optimum load, fill factor (FF), peak power (Pmax), and maximum efficiency (η) of the cell found on clear, cloudy and harmattan days, and compares these with the manufacture's data sheet.

Also, efforts have been made to determine the temperature coefficients of Voc, Isc and Pmax of the solar cell for ranges of ambient temperatures found in the local environment at about 1 sun ($\simeq$1 kw/m^2) insolation. The results obtained have been summarized in Table 2 (Bajpai et al 1986). The expected power variations in the output of the cell due to ambient temperature fluctuations at the same value of solar insolation have also been reported. In continuation of above studies, in this paper, an attempt has been made to study the device physics of silicon solar cell using basic equations of mainority carriers with its boundary conditions, and the series resistance (Rs) of the monocrystalline silicon solar cell and how it is affected in local climatic conditions.

Table 1: Manufacturer's and observed parameters of the cell.

Climatic Condition	**Insolation (Kw/m^2)**	**Voc**	**Isc**	**Vmp**	**Imp**	**Optimum**	**Fill factor**	**Peak power**	**Max. efficiency**
Manufacturer's Curves	0.25 0.50 0.75 1.0	0.45 0.47 0.49 0.50	0.5 1.0 1.5 2.0	0.38 0.40 0.41 0.41	0.425 0.85 1.35 1.825	0.89 0.47 0.30 0.20	0.72 0.75 0.75 0.75	0.16 0.34 0.55 0.75	8.2% 8.7% 9.4% 9.5%
Clear day	0.25 0.50 0.75 1.0	0.525 0.545 0.57 0.59	0.70 1.10 1.45 1.80	0.38 0.39 0.40 0.41	0.575 0.825 1.20 1.55	0.66 0.47 0.33 0.26	0.59 0.54 0.58 0.60	0.22 0.32 0.48 0.64	11.1% 8.2% 8.2% 8.1%
Cloudy day	0.25 0.50 0.70	0.49 0.50 0.51	0.625 0.825 1.025	0.28 0.30 0.34	0.55 0.70 0.85	0.51 0.43 0.40	0.50 0.51 0.55	0.15 0.21 0.28	7.8% 5.4% 4.9%
Harmattan day	0.25 0.50 0.75	0.51 0.53 0.54	0.45 0.70 0.825	0.32 0.34 0.36	0.375 0.60 0.70	0.85 0.57 0.51	0.52 0.55 0.57	0.12 0.20 0.25	6.1% 5.2% 4.3%

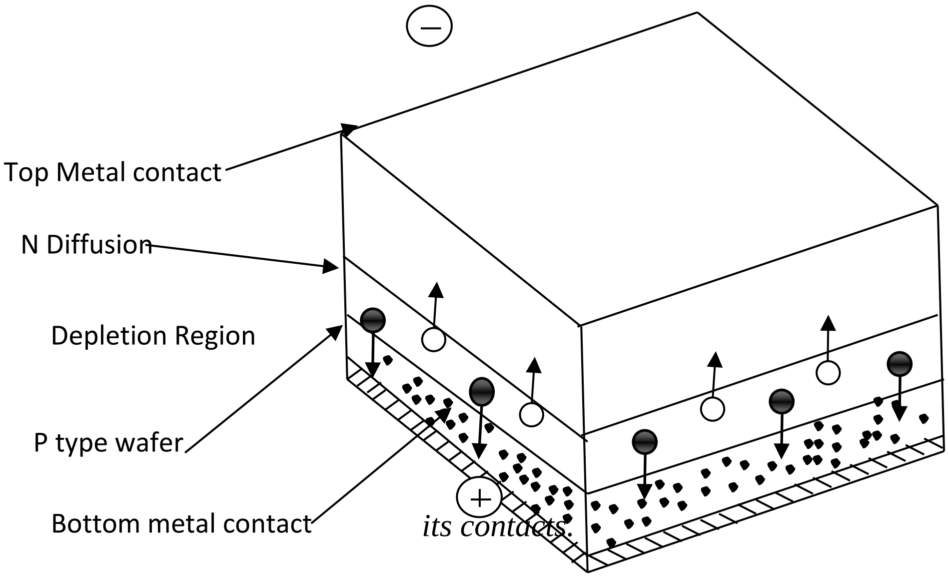
Table 2: Temperature coefficients of the cell.

Manufacturer's values **Reference temp---- 25^{o}c**	**Observed values** **Reference temp---- 35^{o}c**
Temperature coefficient – 0.4% ^{o}c of Voc	-0.36%^{0}c (-2.2 mV^{0}c^{-1})
Temperature coefficient of Isc + 0.1%0c	+ 0.07%0c (+1.2 mA^{0}c^{-1})
Temperature coefficient of Pmax	-0.52%^{0}c (-3.3mW ^{0}c^{-1})

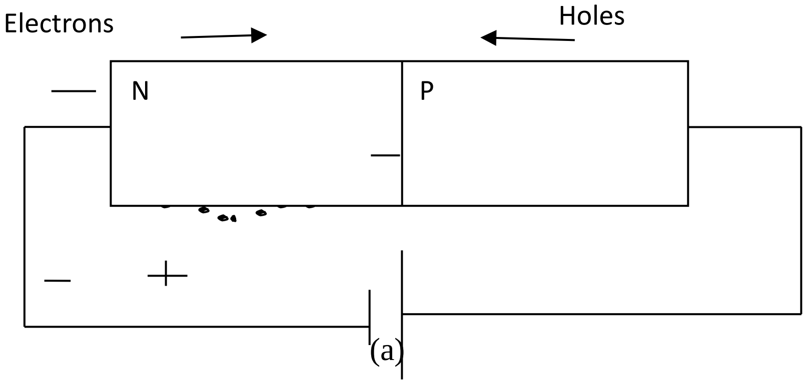
Device Physics of Silicon Solar Cells Silicon Solar Cells

Commonly most silicon solar cells are configured in N-P junctions or vice versa (S.M.SEZ 1981) in one side and N^+-N-P^+ structure (or vice versa) for double sides named bifacial silicon solar cells (Madougou, et al 2007). Silicon solar cells have all contacts on the back of the cell.

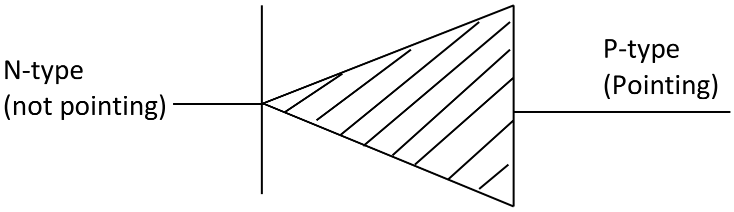
Figure 1 shows an example of silicon solar cell with its contacts.



Monofacial silicon solar cell N-P junction or a P-N junction is a one side solar cell (Shockley, 1949). When a P-type placed in intimate contact with on N-type a diffusion of electrons occurs from the region of high electron concentration (N-Type) into the region of low electron concentration (P-type). Figure 2 shows the N-P junction and its forward biased with its corresponding diode schematic symbols and its I-V characteristic curve.



(a)



(b)

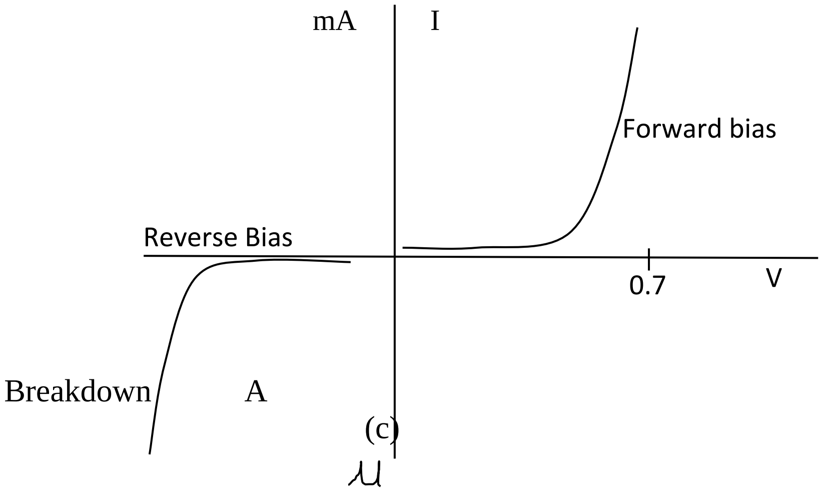


Fig 2. N-P junction:
(a) Forward biased N-P junction
(b) Corresponding diode schematic symbol

Equivalent Circuit of Tthe Solar

To understand the electronic behaviour of solar cell, it is useful to create its model which is electrically equivalent at the solar cell. Because no solar cell is ideal, a shunt resistance and a series resistance component are therefore added to the model to have the equivalent circuit. This equivalent circuit of the solar cell is based on discrete electrical components.
Fig3. Shows an example of an equivalent circuit of a solar cell with one diode.

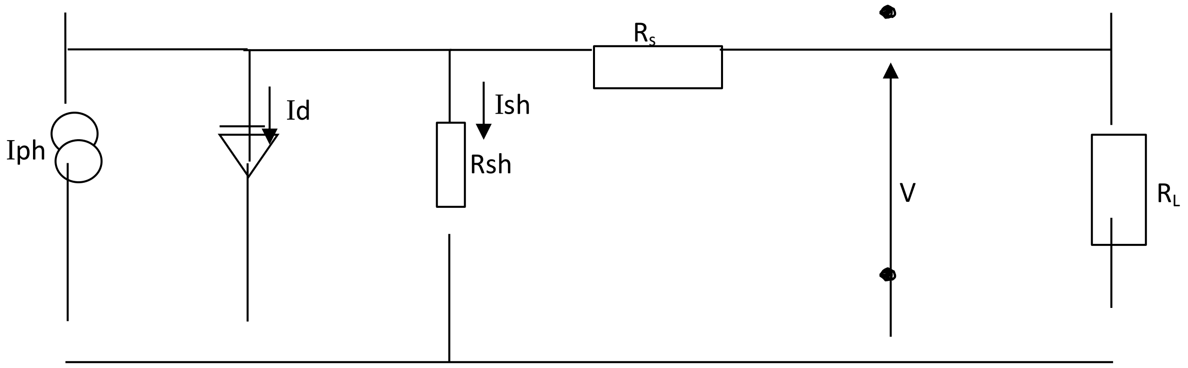


Fig 3: Equivalent circuit of the solar cell with one diode

For the practical analysis of the solar cell performance the dark current-voltage (I-V) characteristics curve is shifted down by a light generated current I_L resulting in the illuminated I-V characteristics.

The I-V characteristic of a single junction P-N under illumination can be written as follows.

I kT (1)

And the dark current density of the P-N junction by

$$I_{dark} = I_o \left[\exp\left(\frac{qv}{kT}\right) - 1\right] \qquad (2)$$

Where, Io is the reverse saturation current density, V the voltage and T is the absolute temperature.

Equation (1) illustrates that at any given external voltage, series resistance increases the current lost through injection in the diode.

3.1 Determination of series resistance and analysis cap.

The series resistance of a solar cell may be simply determined in simulated sunlight by the method of wolf and Rauschenbach

$$R_{sh} = \frac{Vco - v}{I} \qquad (3)$$

The shunt resistance is given by (wolf, M et al 1963)

$$R_{sh} = \frac{V}{Isc - I} \qquad (4)$$

Also, power generated for the cell is

$$P = VI \qquad (5)$$

The fill factor is given by (Shockley, 1949)

$$FF = \frac{Vmax\ Imax}{Vco\ Isc} \qquad (6)$$

Where Vmax and Imax are voltage and current at maximum power point respectively. Vco is the open – circuit voltage and Isc is the short circuit current.

The I- V characteristics of cell are traced at two different insolation values and close temperature range (within $\pm$ 0.5^0c in the range of 23 to 27^0c).

A point is chosen on each characteristic, preferably near the 'knee' of the curve where the current has the same increment $\triangle$I, below the short-circuit current. Rs can be calculated from (3). In the present case, the same method has been applied to actual atmospheric conditions with some necessary modifications. The previously plotted I-V curves of the solar cell for 0.25 kw/m^2, 0.50kw/m^2, and 0.75kw/m^2 solar insolation (within the range of $\pm$ 0.50kw/m^2 of each value of insolation) have been used to determine the series resistance of the cell in clear sky conditions.

(Figure 4).

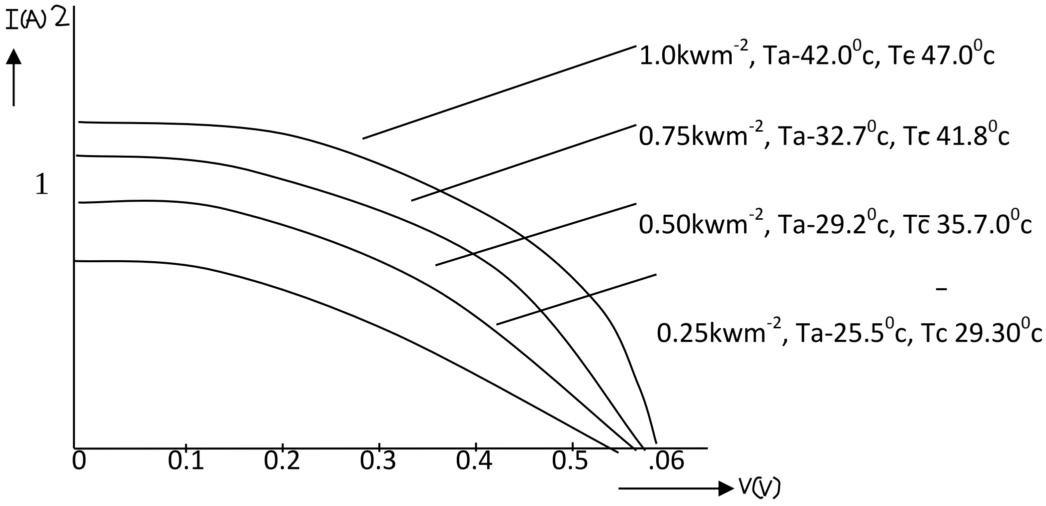


Fig. 4: Observed I – V curves for clear sky conditions.

(Knowing that the working temperature of the solar cell (Tc) depends exclusively on the irradiance, H and on the ambient temperature (Ta) according to the relation

$T_c = T_a + C_I H$

In plotting these I-V curves, the solar insolation, the ambient temperature and the cell temperature were monitored using bimetallic recording pyranometer, thermograph and probetype digital thermometer respectively. Due to considerable fluctuations in the cell temperature at different insolation values, all the short – circuit currents and voltages for $0.25kw/m^2$ and $0.75kw/m^2$ insolation have been projected to values whose temperature is equal to the temperature of $0.50kw/m^2$ insolation.

Using the observed coefficient values given in table 2. Equation (3) has been used to determine R_s for three combinations of curves: $0.25kw/m^2$ and $0.50kw/m^2$, $0.50kw/\ m^2$, a mean has taken for three values of R_s.

For clear sky conditions, the mean value of R_s has been found to be 0.039ohm similar method has been applied to calculate the mean R_s value for average harmattan sky conditions (figure 5) and cloud sky conditions (figure 6), and values obtained are 0.109ohm and 0.109ohm respectively.

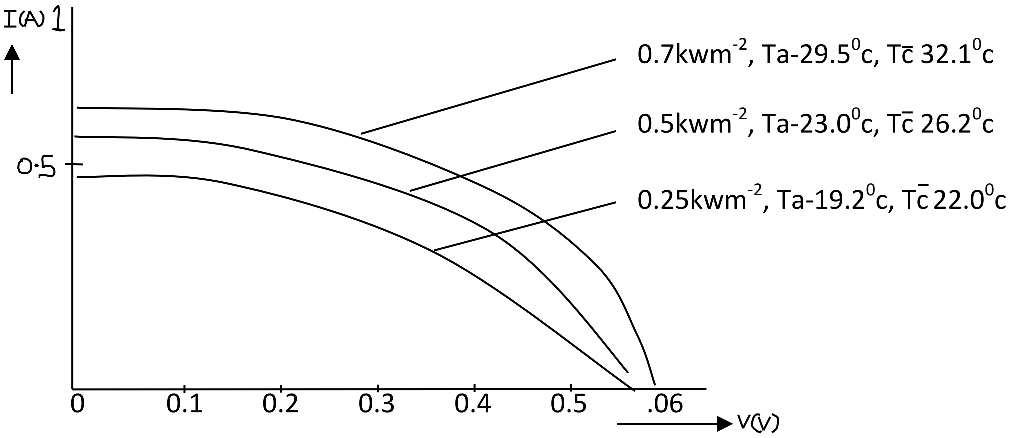


Fig. 5: Observed I-V curves for- Average Harmattan conditions.

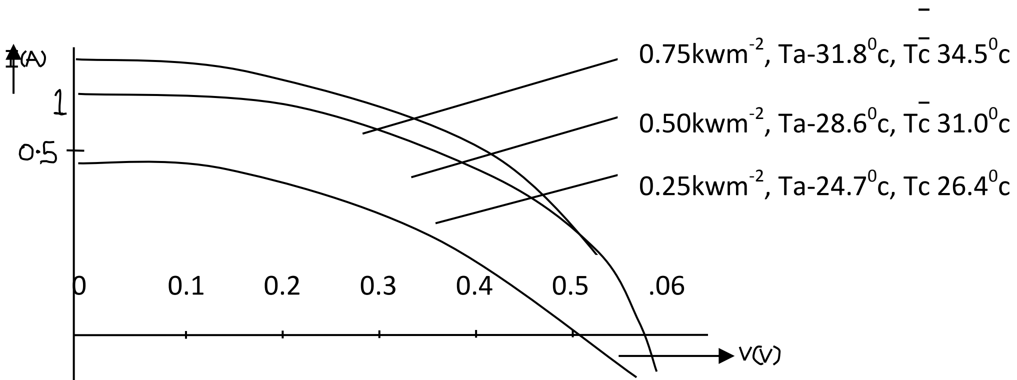


Fig. 6: *Observed I-V curves for cloudy sky conditions*

Manufacturer's I-V (Figure 7) are plotted for a constant cell temperature of 25^0c. Hence, the temperature compensations for short-circuit current and voltages are not required. These curves have given the mean series resistance value of 0.02 ohm taken for same combinations of solar insolation value. Although the three values of R_s Obtained from manufacturer's curves show small dispersion, such dispersion is quite high in case of clear, harmattan, and cloudy day curve values. Further, the mean R_s value of the cell for clear, harmattan and cloudy sky condition are quite in disagreement with the mean value obtained from the manufacturer's data sheet.

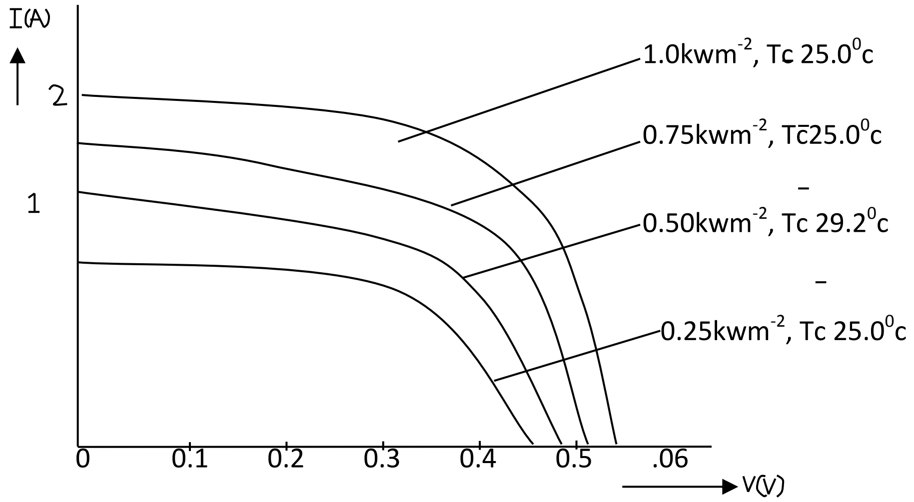


Fig 7: *Manufacturer's I-V curve*

A number of parameters differ in actual atmospheric conditions compared to simulated conditions. Such difference is still greater for harmattan and cloudy sky conditions due to parameters like humidity, and presence of water vapour and aerosols in the atmosphere.

The above implies that the functional series resistance of solar cell at a site, being a lumped quantity, depends on many parameters. Some of these parameters can be identified here as cell I-V curves, solar insolation level, temperature, atmospheric conditions and humidity.

Basic Equations of Minority Carriers Transport

The basic equations describe the behaviour of the excess minority carriers in the base of the solar cell under the influence of an electric field and /or under illumination; both cause deviations from thermal equilibrium conditions. These equations can be expressed on one or two dimensions. This study is on one dimension.

Poisson Equation

The Poisson equation relates the gradient of the electric field E to the space charge density . According ρ to Shockley (1949) it is given as

$$-\frac{d^2\phi(x)}{dx^2}=\frac{dE(x)}{dx}=\frac{\rho}{\varepsilon_o\varepsilon} \qquad (7)$$

Where, O /is the electrostatic potential E_0, is the permittivity of free space and is the static relative permittivity of medium.

In the same conditions, the electrons' current density I_n and the holes' current density I_p are obtained as follows;

$$I_n = +q\mu_n n(x)E(x) + qD_n \frac{d_n(x)}{dx} \longrightarrow 8$$

$$I_p = +q\mu_p P(x)E(x) + qD_p \frac{d_p(x)}{dx} \longrightarrow 9$$

Where, q is the elementary charge, u_n and u_p are the mobility's of electrons and holes, D_n and D_p are the diffusion constants related through Einstein relationships.

$$D_n = \frac{KT}{q\mu_n}; D_p = \frac{KT}{q\mu_p}$$

K is the Boltzman Constant

Continuity Equation

When the solar cell is illuminated, the continuity equation related to photogenerated excess minority carriers density $\delta n(x)$ in the base region of the cell is given by (Sissoko et al, la 1996)

$$\frac{\partial^2 \delta n(x)}{\partial x^2} - \frac{\delta n(x)}{L^2} + \frac{G(x)}{D} = 0 \longrightarrow 10$$

Where, D is the excess minority carriers diffusions constant and L is their diffusion length. G(x) is the carriers generation rate in the base

The solution $\delta n(x)$ of the continuity equation is well defined by the boundary conditions.

Boundary Conditions

According to Sissoko et al (1996), the boundary conditions defined by the minority carriers recombination velocities are;

- The emitter-base junction at x = 0

$$\left.\frac{\partial \delta n(x)}{\partial x}\right|_{x=0} = \frac{sf\,\delta n(o)}{D} \longrightarrow 11$$

- The back-surface of the base at x = H

$$\left.\frac{\partial \delta n(x)}{\partial x}\right|_{x=H} = \frac{-sf\,\delta n(H)}{D} \qquad \longrightarrow 12$$

Where, Sb is the minority carriers recombination velocity at the back surface and Sf is the minority carriers recombination velocity at junction.

Effect of Lead and Contact Resistances

Two important factors in the solar cell measurements are:

- The resistance in the cable leading from the solar cell to the resistance load,
- The resistance resulting from poor electrical contact to the cell with metal probes: Both of these cause a substantial error in the measurements, in effect adding series resistance to the cell and depressing the knee of the I-V curve

In the present study, the researcher succeeded in reducing the series resistance of the measuring circuit (Figure 3) to a value of 0.1Ohm by incorporating the use of two separate pairs of wires leading from four separate probes that make contact with the cell terminals and the current and voltage measuring equipment's. Still, this resistance of cell at certain insolation values, constitutes a substantial part of the corresponding optimum load values and hence reduced values of external load for peak power operations. It has also been observed that the larger value of contact and wiring resistance cause a gap in the I-V curve portion near the short-circuit current. However, such problem can be overcome by incorporating a "back bias".

Conclusion

The series resistance of the monocrystalline silicon solar cell, which is a lumped quantity, was found to vary with solar insolation level for a particular day. The mean series resistance of the cell for Harmattan and cloudy days are very high compared to the value obtained from the manufacturers I-V curves for simulated conditions.

The mean R_s value for a clear day is also found to be higher. The lead and cable resistance of the measuring circuit can cause deviation from actual I-V curve, if it is not kept to a very low value. Basic equations describe the behaviour of the excess minority carriers generated in the base of the solar cells. To understand the electronic behaviour in the study, the solar cell is modeled in an equivalent circuit containing a shunt resistance and a series resistance. In some cases, if care is not taken, the resistance of the lead cable together with the series resistance of the cell can even be higher than the optimum lead value.

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