Journal of Engineering and Applied Sciences 1 (2) : 82-86, 2006

Performance Evaluation of a PV Module Using Computer-Aided Ray Tracing Technique

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Abstract: The characteristics and performance of solar cells and hence the solar modules have been evaluated using computer aided Ray Tracing Technique. A computer simulation program using programming language C was developed to generate sun rays of various illuminations and allowing the rays to intercept sequentially with the active regions of the solar cells of a module. The results of the simulation provide us with the I-V characteristic curves of the module for different values of temperature. The series resistance, Fill Factor (FF) and the optical efficiency of the module have been determined with a view to sizing of module in Photovoltaic Power System.

Key words: Performance, module, computer aided, tracing technique

INTRODUCTION

Photovoltaic array (or module) is the heart of a PV system. During system sizing, PV system designer should know the typical current-voltage (I-V) characteristics of the selected type(s) of PV module at various irradiance and temperature. Since identical solar cells are the elementary unit of the PV array or the PV module, the I-V characteristics of a solar cell is enough to determine the total electrical performance of the PV array.

Ray tracing is a viewpoint-dependent rendering method originating from the geometrical optics that computes the visibility and illumination of objects and other elements in a scene by casting a hypothetical ray from the viewer's eye. This technique uses the law of the optics, but does not directly take into account the wave nature of light and its attendant effects of diffraction, dispersion, interference etc.

For the ray tracing formation, a solar cell (or a solar module) is divided into a number of elementary regions. These elementary regions consist of active regions and inactive region. The portions of the solar cell are not covered by the current collecting grid and bus bar are called active portions and these portions can absorb solar radiation and thereby generate current depending on the solar insulation. The inactive regions are those regions that are covered by grid fingers and bus bars. These regions cannot contribute to the current generation. The active regions of the solar cell are allowed to interact with the sun rays of various illuminations. The results of the interaction are simulated to provide output of a module, which enables to determine the I-V characteristics of the module essential for the design of PV Power System.

Determination of active portions of a module basic consideration: A SIEMENS SM50 PV module containing 36 series[1] connected silicon solar cells is considered. Figure 1 shows the structure of the Siemens SM50 module. The module is divided into elementary portions and we developed a ray tracing program, which traces the physical dimensions, such as length and width of the Module and thereby determining the I-V Curve of the PV Module. Once the I-V curve is plotted, we can easily determine loss due to series resistance, optical conversion efficiency and FF (Fill Factor) of the selected Module from its characteristic curve. In developing the simulation program the following assumptions are considered:

- All the cells of a module are identical.
- The width of each hypothetical sun ray is equal to the width of each grid finger, that is, a sun ray can cover an area of $W_f W_f$ cm^2 if W_f were the width of each finger.
- Wave nature of light is neglected.
- The reflection and refraction of glass cover is not considered.

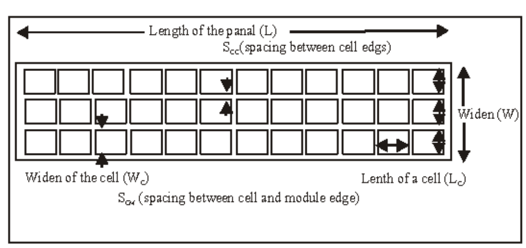

Fig. 1: Gerometrical model of siemens SM 50 module

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- The loss due to optical power loss is ignored.
- The whole module is considered as pixel matrix of order R×C.
- The temperature dependent reverse saturation current (I_o) is considered to be fixed.

Basics of modeling:

- The performance of single crystalline Si solar cell in AM 1.5, under the irradiance of 1000 $W.m^{-2}$ and the cell temperature of 28°C is----
- 1 cm^2 active area can generates the I_{sc} of about 35 mA[2] (1)
- The open circuit voltage

$$V_{oc} = KT/In\ [I_{CC}/I_0\ (E_g\ ,L_d\ ]^{[3]} \qquad (2)$$

where

K = Boltzmann constant(1.38 $10^{-23}J.K^{-1}$),
T = the absolute temperature of the module,
q = charge of a electron (1.6 10^{-19}),
I_o = reverse saturation current of a diode,
E_g = energy band (1.1eV for Si),
L_d = electron diffusion length (40ìm)

- Array Open Circuit voltage:

$$V_{oc(array)} = V_{oc1(cell)} + V_{oc2(cell)} + \text{---} + V_{ocK(cell)} \qquad (3)$$

Where

K = total number of series connected cell

- **Maximum output power:**

$$P_m = V_m I_m = f\ V_{oc} I_{sc}\ ^{[4]} \qquad (4)$$

where

$$V_m = V_{OC} - V_l\ In\ (1 + V_m / V_l)$$

and

$$I_m = I_{SC} - [\exp(V_m/V_l) - l];\ V_l = KT/q \text{ and } f = \text{fill factor}$$

- Aperture efficiency = $\dfrac{P_m}{(A_a \times I_o)}$ [5] (5)

- Total area efficiency = $\dfrac{P_m}{(A_T \times I_o)}$ [5] (6)

Where A_a = active area, A_T = device area, and P_{In} = input light power

Ray tracing formation: For ray trace formation[6] the total area of the Photovoltaic module is considered as a pixel matrix of the order of R×C: R = (L/W_f), number of pixel along the length of the module and C= (W/W_f), number of pixel along the width of the module, where L = length of the module (in cm), W = width of the module (in cm),Thus the total number of pixels in the module is N = R×C and the area of the each pixel is $W_f\ W_f\ cm^2$.

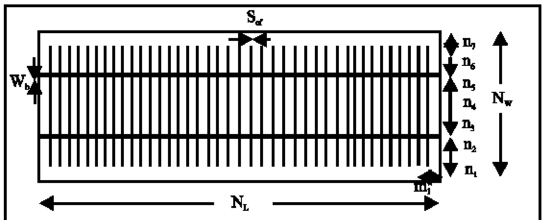

Fig. 2: Geometrical model of a cell of SM 50 module

Fig. 2: Geometrical model of a cell of SM50 module

A sun ray falls on the plane of the module and each sun ray covers one pixel. Thus N numbers of sun rays are fall on the module. When a sun ray falls on an active pixel, the P-N junction and thereby generating current according to its full conversion efficiency absorb the ray. When a sun ray falls on an inactive pixel, the ray is reflected and generates nothing.

Since the number of cell along the length of the panel is m,

Thus,

$$\text{Length of each cell } (L_c) = [L - 2S_{cm} - (m-1)S_{cc}]\ /m \qquad (7)$$

Where

S_{cm} = spacing between cell and module edge (in cm)
S_{cc} = spacing between cells (in cm)

Therefore, number of pixel along the length of the cell

$$N_L = (L_c / W_f) \qquad (8)$$

where

L_c = length of a cell(in cm)

Again, since the number of cell along the width of the panel is n,

Thus, Width of each cell (W_c)=[W- $2S_{cm}$-(n-1)S_{cc}] /n

Therefore, number of pixel along the width of the cell

$$N_W = (W_c / W_f) \qquad (9)$$

Number of pixel in a bus bar

$$N_B = (W_b / W_f) \qquad (10)$$

Where

W_c = width of a cell (in cm)
W_b = width of each bus bar (in cm)

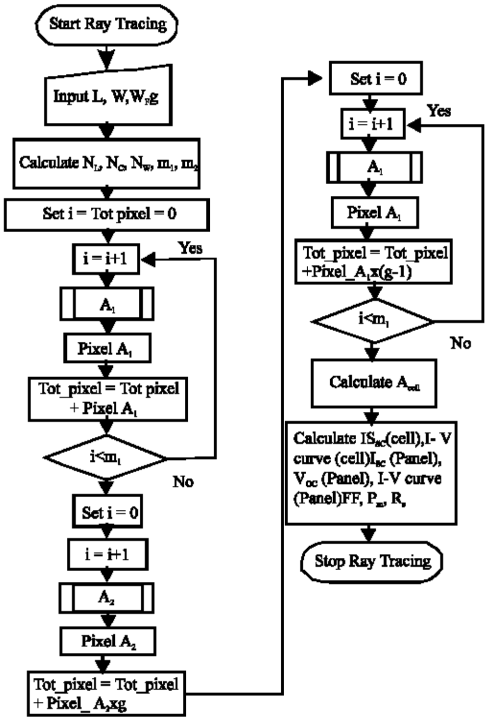

Fig flow chart (mian program) for determining active area of the cell and panal, there by dermining the I_{SC}(cell), I-v Curve (Cell), I_{SC} (Panel), V_{OC} (Panel), I-V curve (Panel), FF, P_m, R_s

In the Fig. 2 the pixel points can be expressed as follows:

n_1 = (S_{cf}/W_f)
n_2 = (N_W/4)–(N_B/2)
n_3 = no_W_b
n_4 = [N_W/2–N_B]
n_5 = n_3
n_6 = n_2
n_7 = n_1
m_1 = n_1
m_2 = [N_L - 2m_1] / (g-1)

where

S_{cf} = spacing between cell and finger edge(in cm)

g = number of grid finger (in cm)

Now, the general expression for the active area of the cell is

$$A_{cell} = (W_f \times W_f) [(n_1+n_2+n_4+n_6+n_7) \text{ x } (2m_1+(g-1) m_2) +g (n_1+n_7)] \quad (11)$$

Determination of electrical chrematistics of the module: Short circuit current of the cell, $I_{sc\,(cell)} = 35 \times A|_{cell}$

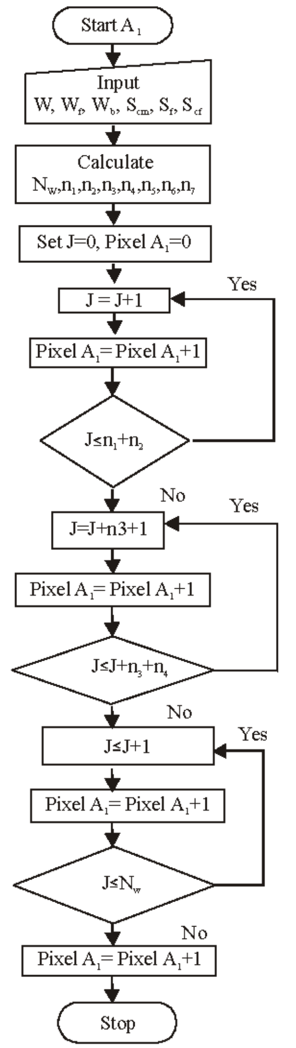

Figure subroutine A_1 determines active pixel anlong the width of the cell

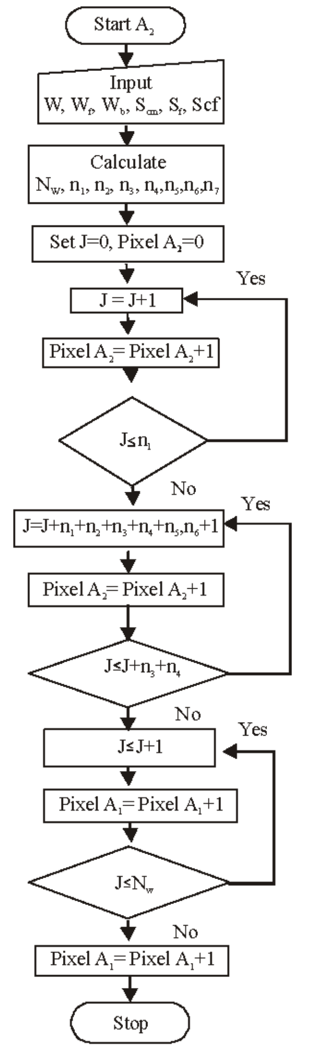

Figure subroutine A_2 determines active pixel anlong the width of the cell

Data for I-V electrical characteristics of solar module

Open circuit voltage of the cell, V_{oc} = KT/q In [$l_{CC}/l_O(E_g, L_d)$]

Since, all the cells are connected in series in SM50 Module, thus the Array short circuit current is

$$I_{sc\,(array)} = I_{sc\,(cell)}$$

and, Array open circuit voltage is

$$V_{oc(array)} = \sum_{i=1}^{mxn} V_{oc(cell)}|\, i$$

Physical characteristics							
Brand/model	L (cm)	W (cm)	Wb(cm)	Wfcm	Fs(cm)	Scc(cm)	Scm(cm)
Siemens SM50	129.29	33.02	0.56	0.015	0.26	0.8	0.9

Electrical Parameters of SIEMENS SM50

Effect of light intensity

Room temperature =25^{0}C

Light intensity	Isc(A)	Voc(v)	Im (A)	Vm(v)	Pm(W)	efficiency
1000	3.313	18.706	3.148	15.339	48.29	11.31%
800	2.65	18.51	2.513	15.17	38.124	11.16%
600	1.988	18.233	1.88	14.951	28.101	10.97%

Effect of temperature

Irradiance=1000W/m^2

Temperature(C)	Isc(A)	Voc(v)	Im (A)	Vm(v)	Pm(W)	efficiency
32	3.313	19.145	3.065	15.699	48.189	11.23%
27	3.313	18.832	3.128	15.442	48.314	11.32%
25	3.313	18.706	3.148	15.339	48.29	11.31%

Determination of R_s

V_2	I_2	I_1	R_s
15.339	2.513	1.88	0.591
15.699	3.065	3.128	0.492

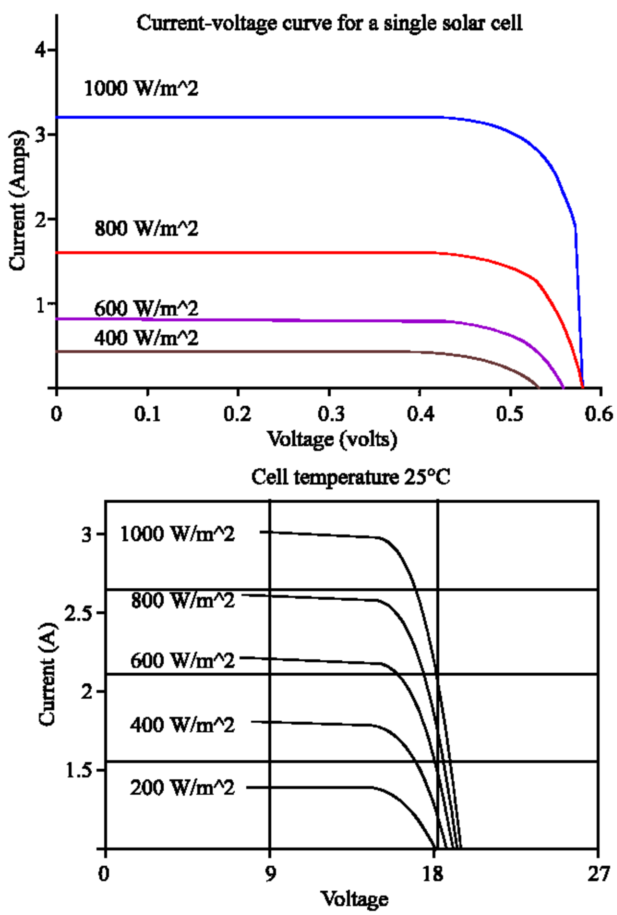

Fig. 3: (a) I-V curve of a single solar cell at various illuminations, and (b) I-V curve of the Siemens SM 50 Module at various illuminations

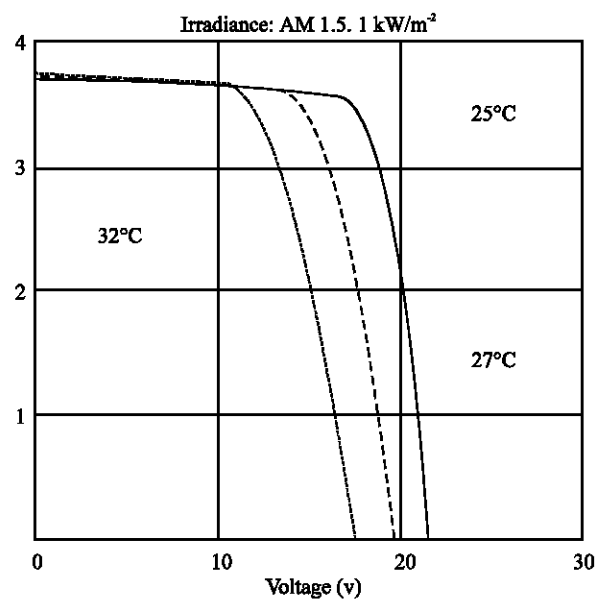

Fig. 4: I-V curves of a single solar cell at various temperature

Table 1: The simulated results and the experimental results

Electrical parameter (at 1000 W/m^2)	Simulated data	Experimental data	Percentage of error
Isc(A)	3.113	3.05[1]	6.3%
Voc(V)	19.992	21.4[1]	6.5%
Pm(W)	48.189	50[1]	3.6%
Efficiency(%)	11.23	12[1]	6.4%
Rs(Ω)	0.591	0.632[1]	6.48%

Now we determine maximum power, P_m, Fill Factor (FF), Aperture efficiency and total area efficiency, Loss due to series resistance.

RESULTS AND DISCUSSION

Figure 3 shows the Effect of Light of Intensity (or irradiance) on the I-V characteristics of a single solar cell and the SIEMENS SM50 PV Module. It is observed in the Fig. 3 that when the irradiance level of light changes, the output short circuit current (I_{sc}) as well as open circuit voltage (V_{oc}) changes. Actually lower irradiance not only reduces current considerably but also reduces V_{oc} slowly. The effect of temperature on the I-V characteristics of a single solar cell and the above SIEMENS SM50 Module has been represented in the Fig. 4. In this case, I_{sc} rises slightly but V_{oc} reduces considerably as temperature goes up. The values of output short circuit current (I_{sc}), open circuit voltage (V_{oc}), Power at maximum power point (P_m) and optical conversion efficiency of the Siemins SM50 Module obtained with the computer simulation program was compared with the experimental data. The Table 1 shows the comparison and percentage of error between the simulated results and the experimental results.

As we have considered the cells in the Module are identical having no optical losses and no loss due to glass cover, the results of I_{sc}, V_{oc}, P_m and optical conversion efficiency of the Module are not the exact replica of that of the Experimental data. Another reason of differing Voc is that the reverse saturation current is considered independent of temperature.

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