A STUDY OF SILICON SOLAR CELLS AND MODULES USING PSPICE REFLECTIONS ON POWER SUPPLY DESIGN

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Abstract– A study of a 100cm^2 silicon solar cell and modules constructed from such series connected cell-strings is carried out using a student evaluation version PSPICE. The study showed that this widely available simulation tool can reveal useful properties of solar cells, and modules, which are relevant to module design as well as the design of power supply regulators and inverters utilized with PV systems.

Keywords: **PV cell, PV module, PSPICE, Power Supply**

I. INTRODUCTION

The importance of photovoltaic cells in the direct conversion of solar energy into electrical energy is well known and well established. As silicon is among one of the most abundant materials available, the interest of producing PV cells from silicon (in particular crystalline Si) material has dominated the industry. Recently, it has been reported that experimental crystalline silicon solar cells have reached a confirmed efficiency of 24.7% and that commercial cells of 17-18% efficiency are now available [1]. Experimenting with actual PV cells in the laboratory is often an expensive and time consuming task. For this reason it is wise to resort to simulation techniques to overcome this problem. Many commercial simulation software already exist in the market [2]. However, such software are not widely available, especially to students.

In this work we have simulated a 100cm^2 silicon cell and modules constructed by connecting up to 31 of these cells in series, using the MicroSim® evaluation PSPICE [3]. The simple study carried out lead to valuable information that would be useful in the design of PV modules and power supply systems utilizing such PV modules as their basic energy source.

II. THE PSPICE SIMULATION PROGRAM

The lumped parameter model of a silicon solar cell used in this work is the equivalent circuit shown in Fig.1,[4], [8]. The solar cell represented by this equivalent circuit may be of the single or polycrystalline type. In this model I_L represents the bipolar current due to light generated carriers that reach the electrical terminals, and D_l represents the p-n junction of the solar cell. R_s is the series resistance that accounts for the overall voltage drop that the carriers encounter in moving from where they are generated to the points of metal contacts (the terminals) of the cell. R_{sh} is the shunt leakage resistance which accounts for the formation of the so called "hot spot" [4], due to the shadowing of a cell in a module.

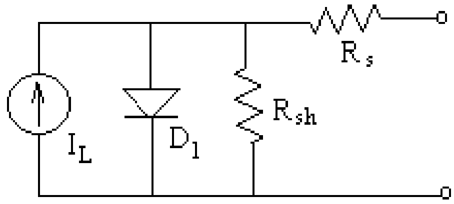


Fig.1 Equivalent circuit of a silicon solar cell

The I-V relation for a single cell related to the above circuit model is given by the equation:

$$I = I_L - I_0\left\{\exp\left[\frac{q(V+IR_s)}{nkT}\right]-1\right\} - \frac{V+IR_s}{R_{sh}} \qquad (1)$$

Where I_L is the current due to illumination of the solar cell, I_o is the dark saturation current, q is the electron charge, n is the so called "ideality factor"[4] or the diode emission factor [5], k is Boltzmann's constant and T is the cell absolute temperature in degrees Kelvin. For a group of N series-connected identical cells that would constitute a basic module, the current through each cell in the group is the same as the current through a single cell (I_{tot} =I). The module voltage V_{tot} is N times the voltage V of a single cell (V_{tot} =NV). In order to develop the I-V relation for the module we can replace the above variables for I and V in (1) by I_{tot} and V_{tot} respectively as shown below in equation (2):

$$I_{tot} = I = I_L - I_0\left\{\exp\left[\frac{q(V_{tot}+INR_s)}{NnkT}\right]-1\right\} - \frac{V_{tot}+INR_s}{NR_{sh}} \qquad \text{........ (2)}$$

The same topology is usually used for the equivalent circuits of the module as for the cell as is suggested by (1) and (2) above [4], [5]. The ideality factor is modified in the manner shown, the series current assumption for identical cells is reasonable. However, the diode currents, R_{sh} , R_s , and the output voltage of the cells combine in no simple way to form the corresponding values of the module parameters since the equivalent circuit of the cell is not linear.

The PSPICE program used in the simulation of the equivalent circuit of Fig.1 is given in Appendix 1. This program is simply modified to simulate modules of 2, 5, 10 and 31 series connected cells[6],[7]. An example of a module obtained by connecting 2-cells in series is shown in Fig.2. The other series connected cell-strings are obtained similarly. The PSPICE input file was modified accordingly to investigate parametric changes in the equivalent circuit, and to show the effect of such changes on the maximum power output and the operating voltage V_m at the maximum power point. The I-V characteristics and the output power curves were obtained using PROBE. The effects of ambient temperature changes were studied using the same input file by taking T as a parameter. In each of the investigations carried out, a set of curves for the I-V characteristics and a set of curves for the output power were obtained as shown in Appendix 2. From these curves the variation of the open circuit voltage V_{oc} and the variation of the operating output voltage V_m were tabulated as shown below in the relevant tables in the following sections.

III. THE SOLAR CELL STUDY

We simulated the solar cell circuit shown in Fig.1 assuming that it represented a 100cm^2 silicon cell using typical parameter values under standard test conditions as suggested in [4]. The main interest in the simulation was to observe and determine the variation of V_m at the maximum power point as the cell parameters are varied.

First, to make sure that the temperature variation was the main factor in determining the output operating voltage [6] we investigated the variation of the maximum output power of the cell for R_s values of 0.001, 0.01, 0.02, 0.03, and 0.04Ω with R_{sh} held constant at 100Ω and the cell temperature constant at 25°C. The ideality factor was taken as n=1.1, and I_0= 1.0x10^{-10} A. The results of this simulation are shown in Table I. Next, we investigated the effect of varying R_{sh} on V_m and V_{oc} for R_{sh} values of 300, 100, 30, and 10 Ohms, at Rs = 0.001Ω and 25°C. Finally, holding R_s at 0.001Ω, R_{sh} at 100 Ohms, I_0 as before, the I-V curves and the output power curves for values of T= 5°C to 85°C in steps of 20°C were plotted for two different cells, first with n =1.1 and next with n=1.5. The value of I_L in all of the above tests was taken as 3.5A. The results of these simulations are given in Tables II,III respectively. As can be seen from the tables, the tests confirmed that the increasing of the cell temperature was the main factor which determines the fall of Vm. These tests also showed that increasing the value of n resulted in unrealistic values for V_{oc}.

As can be seen from these tables, for n =1.1, V_{oc} falls by 1.67mV/°C, V_m falls by 1.75mV/°C, and for n = 1.5, V_{oc} falls by 0.83mV/°C, V_m falls by 1mV/°C. From these results we observe that the fall of the operating voltage V_m/°C is a more critical parameter in design considerations for both values of n. The results also show that n= 1.1 is a more realistic value of the ideality factor for the silicon solar cell as it yields voltage fall rate values closer to known practical values for such cells.

IV. THE SOLAR MODULE STUDY

The module study was based on identical cell strings with no shading on any of the cells. Due to the limitations of the software we were restricted to simulate modules up to 31 series connected cell-strings.

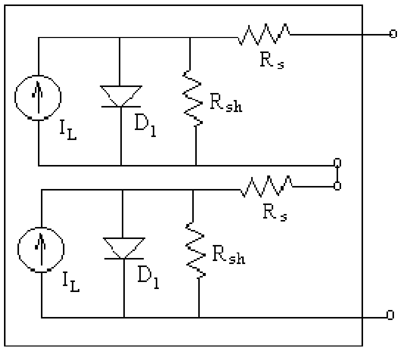


Fig.2 A 2-cell series cell-string module

In practice 36 series cell-strings are usually considered for a 12V power supply system, this limitation was not of major significance in our study. To see the effect of decreasing the number of series connected cells on the output voltage fall rate (mV/°C for V_{oc} and V_m) the tests were carried out for 2, 5, 10 and 31 cell-strings. Each module was tested for n =1.1 and for n = 1.5. The 2-cell module was simulated using the equivalent circuit shown in Fig.2. The equivalent circuits for the other modules were similarly extended. All cells in the module were assumed to be identical and to produce a short circuit current of 3.5A under standard test conditions. The parametric variation tests carried out for the module were similar to those carried out for the single cell. The I-V curves and the variation of output power versus temperature rise were obtained from curves similar to those shown in Appendix 2 and the results are as tabulated in tables IV to VI.

The simulation results for n=1.5 did not reflect realistic values for V_{oc} since they yielded higher output voltage levels than is possible for the type of the silicon cells used. As is observed from the tables the fall in both V_{oc} and V_m is reasonably linear for the indicated increasing temperature values. It is also observed that the value of n is important in the modeling of the cell and modules and that the closer n is to unity the closer is the voltage fall rate to the known practical values. Finally, the fall rates to be considered in power system design should be those of the operating voltage V_m.

TABLE I R_s variation

R_s	0.001	0.01	0.02	0.03	0.04
V_{oc}(mV)	697.21	697.23	697.25	697.265	697.28
V_m(mV)	610	600	600	600	600
P_m(W)	2.0224	2.0178	2.014	2.01	2.0058

TABLE II R_{sh} variation

R_{sh}	300	100	30	10
V_{oc}(mV)	697.4	697.4	697.4	697.4
V_m(mV)	600	600	600	600
P_m(W)	2.0156	2.0156	2.0156	2.0156

TABLE III: V_{oc} Variation for $n = 1.1$

Cell Number	1	2	5	10	31
5 °C	0.73V	1.46V	3.65V	7.305V	22.65V
25 °C	0.697V	1.395V	3.49V	6.975V	21.62V
45 °C	0.662V	1.328V	3.32V	6.64V	20.6V
65 °C	0.631V	1.261V	3.15V	6.31V	19.55V
85 °C	0.597V	1.194V	2.984V	5.97V	18.5V
V_{oc} Fall (mV/°C)	1.67	3.325	8.325	16.69	51.875

TABLE IV: V_m Variation for $n = 1.1$

Cell Number	1	2	5	10	31
5 °C	0.64V	1.28V	3.19V	6.39V	19.8V
25 °C	0.6V	1.21V	3.02V	6.03V	18.7V
45 °C	0.57V	1.14V	2.84V	5.68V	17.6V
65 °C	0.53V	1.06V	2.66V	5.32V	16.51V
85 °C	0.5V	0.99V	2.49V	4.97V	15.42V
V_m Fall (mV/°C)	1.75	3.62	8.75	17.75	54.75

TABLE V: V_{oc} Variation for $n = 1.5$

Cell Number	1	2	5	10	31
5 °C	0.963V	1.926V	4.82V	9.72V	30.15V
25 °C	0.947V	1.894V	4.734V	9.56V	29.65V
45 °C	0.93V	1.861V	4.651V	9.4V	29.17V
65 °C	0.913V	1.827V	4.568V	9.24V	28.67V
85 °C	0.896V	1.793V	4.482V	9.073V	28.15V
V_{oc} Fall (mV/°C)	0.834	1.66	4.23	8.0875	25

TABLE VI: V_m Variation for $n = 1.5$

Cell Number	1	2	5	10	31
5 °C	0.84V	1.68V	4.21V	8.42V	26.09V
25 °C	0.82V	1.64V	4.1V	8.21V	25.45V
45 °C	0.8V	1.6V	4V	8V	24.8V
65 °C	0.78V	1.56V	3.89V	7.79V	24.15V
85 °C	0.76V	1.52V	3.79V	7.58V	23.50V
V_m Fall (mV/°C)	1	2	5.25	10.5	32.375

V. CONCLUSIONS

Although PSPICE has its limitation in the study of more complicated modules and arrays of PV modules, nevertheless it is sufficient to investigate the effects of parametric variations of PV cells and of modules constructed from such cells. It is shown that such study can reveal and quantify the operating voltage drop V_m at the module output at high temperatures. We can thus allow for worst case situations in the design of power supply regulators and inverters of power supply systems that utilize PV sources as their primary sources of energy. This widely available simulation tool can also be used in the teaching of photovoltaics subjects and can substitute for expensive and time consuming experiments.

VI. REFERENCES

[1] M. A. Green, J. Zhao, A. Wang, S. R. Wenham, "Progress and outlook for high-efficiency crystalline silicon solar cells," Solar Energy Materials & Solar Cells 65 (2001) 9-16.

[2] David L. King, James K. Dudley, and William E. Boyson, "PVSIM©: A Simulation Program for Photovoltaic Cells, Modules, and Arrays," Sandia National Laboratories, Albuquerque, NM 87185-0752. Presented at the 25th IEEE PVSC, Washington DC, May 13-17, 1996.

[3] MicroSim® Design Manager, Evaluation Version 8.0, July 1997, MicroSim Corporation.

[4] S. R. Wenham, M. A. Green, M. E. Watt, "Applied Photovoltaics," Centre for Photovoltaic Devices and Systems, University of NSW, Sydney, 1994. Also project 1: "Solar Cell Modelling," project 2: "PV modules," proposed by Univ.of NSW, downloaded from internet July, 2001.

[5] T. Ikegami, T. Maezoono, F. Nakanishi, Y. Yamagata, K. Ebihara, "Estimation of equivalent circuit parameters of PV module and its application to optimal operation of PV system," Solar Energy Materials & Solar Cells, 67 (2001) 398-395.

[6] Tomas Markvart (Editor), Solar Electricity, John Wiley & Sons, 1994.

[7] John Keown, "PSpice and Circuit Analysis," Prentice Hall, 1993.

[8] P. T. Krein, "A Simple Solar Cell Model," IEEE Power Electronics Society Newsletter, April 2001.

APPENDIX I

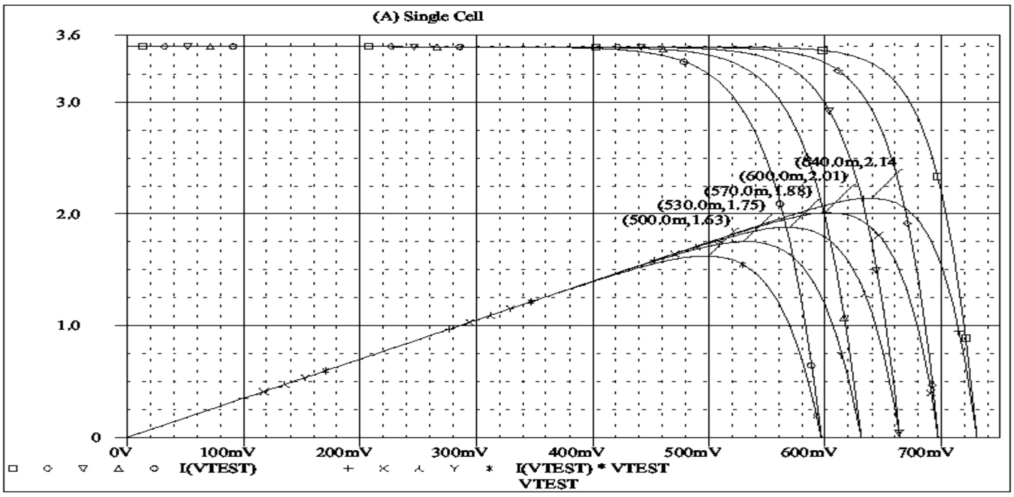
A convenient way to obtain the I-V characteristics of the simulated circuit is to insert a voltage source at the output terminals and vary the voltage from zero to a value near the expected open circuit voltage. Since Spice will automatically determine the current at each voltage level we would be able to plot the output curve using Probe.

The basic PSPICE input file that we used throughout with simple modification is as follows:

```
*solarcell
IL 0 1 DC 3.5
VTEST 2 0 PWL(0 0 0.7 0.7)
D1 1 0 DIODE
RS 1 2 0.001
RSH 1 0 100
.MODEL DIODE D(Is=0.1N Rs=0.001 N=1.1)
.TEMP 5 25 45 65 85
.DC VTEST 0 0.8 0.01
.PLOT DC I(VTEST)
.PROBE
.END
```

APPENDIX II

In this appendix we show a typical I-V characteristics and output power curves obtained with parametric variations (for the figure shown the parametric variation is that of the cell temperature). The figures obtained in the tables were obtained from such relevant curves.



I-V curves and output power curves under parametric variation (cell temperature)