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## **AC 2011-212: APPLIED MODELING OF SOLAR CELLS**

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I have been teaching and researching Electrical Power Systems for over 25 years, and currently I am a professor of ECE. Published over 20 technical papers and given several presentations related to the "smart grid" and electric power systems. Consulting with several major corporations has been accomplished in the areas of power electronics and solar energy. I am the lead faculty member of the Electric Power Systems Program. I have established the electrical machines and microprocessor-relay laboratories and power electronics laboratory (in progress). Research interests are solar energy, wind energy, power electronics, protection and teaching. I am Senior Member of IEEE, HKN (adviser), ASEE campus representative. I am the recipient of the "Distinguished Engineering Educator Award," given by the San Fernando Valley Engineer' Council, February 2010, Los Angeles CA.

## **Modeling of Solar Cells Utilizing PSpice and Matlab-Simulink in the Classroom**

*Abstract:*-This paper discusses the educational benefits of utilizing the mathematical models of Solar Cells in an electrical power systems curriculum. The mathematical model of Solar Cells and their simulation are discussed by using Pspice and Matlab-Simulink software. From the model we can define the relationship between current and voltage, the affect of temperature, irradiance (solar insolation), series resistance, and shunt resistance. Photovoltaic power can be generated for residential, commercial and industrial usage in the form of DC power and usually it is inverted to AC power via power electronics. These simulations can be used for teaching purposes. The code is provided to the students so that they can focus on the results. We believe that this paper discusses solar cells in the context of teaching.

The impact of utilizing Pspice and Matlab-Simulink on student learning is assessed by implementing future pre & post evaluation tools.

The electric power industry will require an estimated 11,000 power engineers by the year 2014. As of today there are about 500 college degrees granted in power engineering. Thus, schools are quickly falling behind in the ability to output the appropriate amount of Power Engineers into the workforce. Typically, a Power Engineer has a sub-specialty, such as renewable energy. Knowledge of solar generation, mainly, creates a well-rounded Power Engineer who is more marketable and in-demand by the utility industry and by other Engineering groups.

*Introduction:*-It is predicted that by the year 2050 emissions of CO<sub>2</sub> will double [2]. Thus, low carbon emission technologies for generation of electricity will be of great importance. One of those technologies is solar panels. The G8 in 2008 mandated to the International Energy Agency (IEA) to develop a road map for the most important technologies focusing on “technology” development and dissemination worldwide. Since PV (Photovoltaic) energy is viewed as one of the cleanest technologies and the abundance of solar energy is everywhere, the IEA has created a roadmap for this technology. Use of PV or solar energy has been increasing at a rate of 40% annually worldwide since year 2000 [2], so, by the year 2050 it is proposed to generate 11% of the world power using solar energy or 4500 TWh/year (3000GW) and will have a reduction of 2.3 gigatonnes (Gt) of CO<sub>2</sub>/year. This is a very ambitious goal that very likely will not be achieved, but, getting close to it will be a major success in terms of clean energy and the environment. It is also predicted that by the year 2020 we will achieve a cost balance between PV and the power grid.

Solar energy is the most abundant source of energy. Suffice to say that one hour of solar energy that hits the surface of the planet is equivalent to an entire year of electric energy consumed by the entire world. There are three main solar technologies available, these are: PV-direct conversion of sunlight, CSP- concentrated solar power, SHC- Thermal collectors for heating and cooling. In 2008, 0.1% of the global generation of electricity was produced by PV.

PV-cell-The PV cell is a semiconductor device. Several cells are interconnected in series or parallel or series-parallel configuration, depending on the application and the manufacturers. These interconnections form a module (panel) usually rated between 50 to 200 W. These modules can be interconnected to create a PV system or plant reaching outputs in the KW and even MW.

PV cells can be made of crystalline Silicon (c-Si) and thin films. Also there is a new technology called CPV-concentrated photovoltaic. The c-Si has about 80% to 90% of the PV market globally. Thin films have about 10% of the global market and these films can be made of: amorphous (a-Si) and micromorph silicon (a-Si/ $\mu$ c-Si) Cadmium Telluride (CdTe), Copper indium Diselenide (CIS) and Copper Indium Gallium Diselenide (CIGS) [2].

PV-cell conversion efficiency-It is defined as the ratio between electrical power output and the incident solar energy/sec. Thus the efficiencies of some PV technologies are described in the table below [2]. The costs of PV are measured in dollars/watt.

Wafer based c-Si		Thin Films		
sc-Si	mc-Si	a-Si; a-Si/ $\mu$ c-Si	CdTe	CIS/CIGS
14%-20%	13%-15%	6%-9%	9%-11%	10%-12%

Why simulation in Pspice?-Teaching of electrical engineering (EE) includes simulation of electrical and electronic circuits. Pspice has become the standard industrial simulator and consequently it has become the standard in most of the EE programs in the United States. There are several other simulators that are quite good but not as complete, easy to learn and with a free demo as Pspice. The free version has all the features of the professional version, except for the number of nodes that can be utilized. One of the major advantages of this simulator is its library. Most semiconductor devices, analog and digital components are modeled by the manufactures in a way that they can be included in the Pspice library.

Why simulation in Matlab?-Matlab has become the “mathematical” tool for simulation in all areas of engineering. EE and ME rely heavily in this tool. It is very powerful, especially when a toolbox is included. There are several other software vendors that have solar cell simulations which are utilized in industry, such as ETAP and PSCAD.

Solar cell model-The solar model that is studied and analyzed is shown in fig. 1. It is quite a simple circuit and easy to model. The modeling results are accurate and therefore they validate the goodness of the model. Semiconductor technology analysis is kept to a minimum since the purpose of this paper is to demonstrate a simple, yet effective way to teach the modeling of solar cells using Pspice and Matlab.

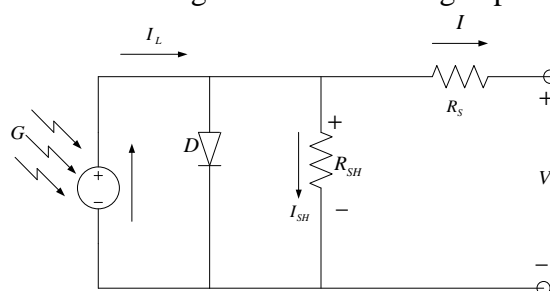


Fig. 1 Solar Cell equivalent circuit

The circuit in fig. 1 has a current source that is in parallel with a diode. It is necessary to indicate that the output of the current source is directly proportional to the photocurrent “ $I_{ph}$ ” (exposure to light, “irradiance”). The internal losses in the circuit are represented by a resistor, “ $R_s$ ” and the leakage current to ground is represented by “ $I_{sh}$ ” which can be neglected for the sake of simplicity and with very little compromising the accuracy of the model.

The output current of the solar cell,  $I$ , is the difference of the solar cell short circuit current and the diode current, assuming that the leakage current is negligible,  $I_{sh} = 0$ , the current at the diode can be obtained by utilizing the following equation

$$I_D = I_0 \left\{ e^{\frac{V}{V_T}} - 1 \right\} \quad (1)$$

Where “ $V_T$ ” is the thermal potential and it is equal to  $\frac{KT}{q}$  and “ $K$ ” is the BOLTZMAN constant, “ $q$ ” is the charge of an electron and “ $T$ ” in  $^{\circ}C$  is temperature, and “ $V$ ” is the applied voltage.

$$I = I_{sc} - I_D \quad (2)$$

$$I = I_{sc} - I_0 \left\{ e^{\frac{V}{V_T}} - 1 \right\} \quad (3)$$

The open circuit voltage occurs when  $I = 0$  and therefore we obtain the following equations:

$$I = 0 = I_{sc} - I_0 \left\{ e^{\frac{V_{oc}}{V_T}} - 1 \right\}$$

Solving for  $V_{oc}$  yields:

$$V_{oc} = V_T \ln \left\{ 1 + \frac{I_{sc}}{I_0} \right\} \quad (4)$$

Irradiance,  $G$ , is measured in  $\frac{W}{m^2}$  and indicates the amount of solar energy on a surface, thus if we let  $I_{sc} = AJ_{sc}$ , where “ $A$ ” is the area of the surface and “ $J_{sc}$ ” is the short circuit current density, then :

$$irr = \frac{AJ_{sc}}{1000} G \quad (5)$$

Pspice-The Pspice model of equation 5 is obtained from Fig. 2

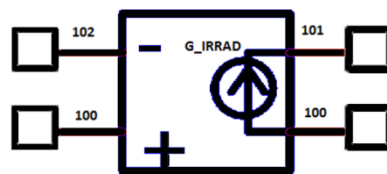


Fig. 2 Model used for irradiance

Equation 5 indicates that the short circuit current is proportional to the irradiance. In Pspice a VCCS circuit is used to model this effect. Fig. 3 shows the Pspice model utilized.

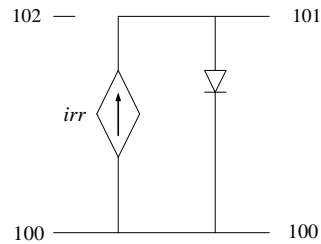


Fig. 3 Pspice Irradiance model

We use a dummy parameter in the code, because this cell model is a sub circuit that will be attached to a circuit and then the required values of the parameters will be included. The code for equation 5 is as follows;

Code, Netlist code for Sub-Circuit

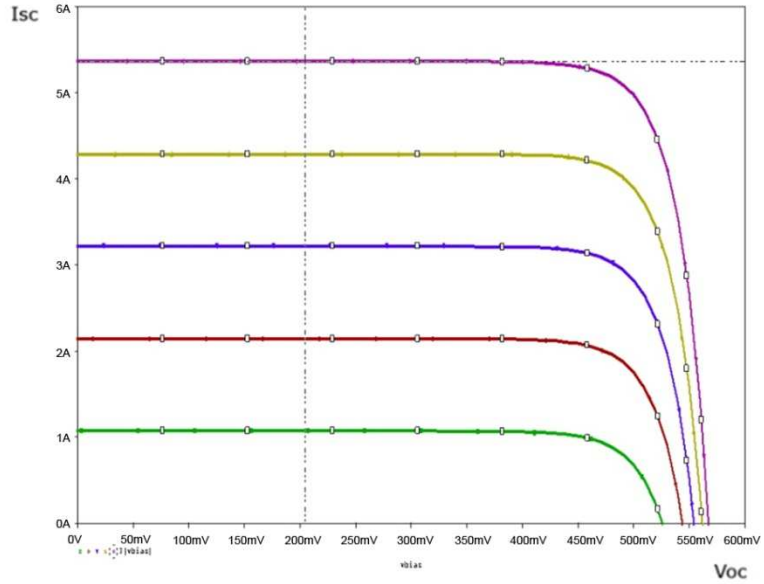
```
*cell.lib
.subckt cell 100 101 102 params: area=1,j0=1,jsc=1
girrad 100 101 value={(jsc/1000)*v(102)*area}
d1 101 100 diode
.model diode d(is={j0*area})
.ends cell
```

Let the diameter of the solar cell be 4 in,  $j_{sc} = 30 \text{ mA/cm}^2$ ,  $j_0 = 1 * 10^{-11} \text{ A/cm}^2$ . Observe that  $I_0 = AJ_0$   
The code for the first simulation is as follows:

Code: Netlist Main Code

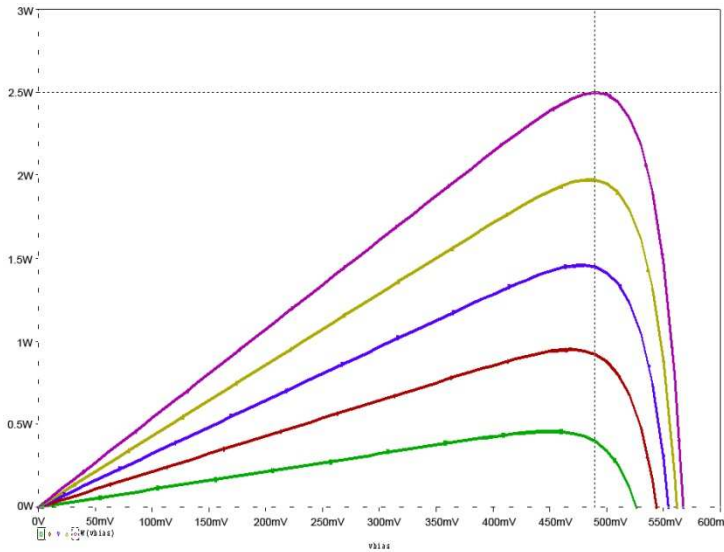
```
*Irradiance.cir
.include cell.lib
xcell 0 31 32 cell params: area=156.25 j0=1e-11 +jsc=0.0343
vbias 31 0 dc 0
.param irradiance=1
virrad 32 0 dc {irradiance}
.step param irradiance list 200 400 600 800 1000
.plot dc i(vbias)
.probe
.dc vbias 0 0.6 0.01
.end
```

Pspice Output:



Probe Cursor	
A1 =	204.245m, 5.3597
A2 =	204.245m, 5.3597
dif=	0.000, 0.000

Fig. 4 I-V Curves at different Irradiance



Probe Cursor	
A1 =	490.094m, 2.4969
A2 =	0.000, 0.000
dif=	490.094m, 2.4969

Fig. 5 Power curves at different irradiance

Observe that each curve corresponds to a different irradiance. So for an irradiance of  $1000 \text{ w/m}^2$  we get approximately 2.5 W maximum output (Approximately 5 A times 0.5 V); therefore from the output we can calculate for a given irradiance the MPPT (Maximum Power Point Tracking) which is calculated as follows:

$$MPPT = V_{max}I_{max} \quad (6)$$

Also from the output we can determine another solar cell characteristic, which is the “fill factor” indicating the quality of the solar cell. This can be calculated as follows:

$$FF = \frac{V_{max}I_{max}}{V_{oc}I_{oc}} \quad (7)$$

Matlab-In this case we use Matlab-Simulink as our simulation software. The solar cell model, similar to the one simulated in Pspice, is described in Fig. 6. The corresponding Simulink circuit is shown in Fig. 7.

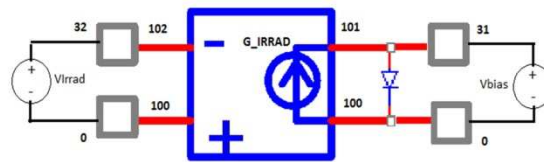


Fig. 6 Solar Cell Model

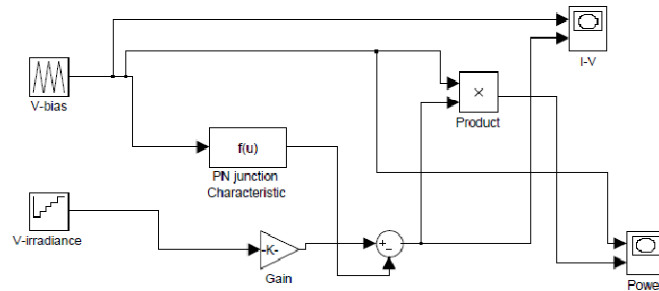


Fig. 7 Simulink block diagram of a solar cell

Output:

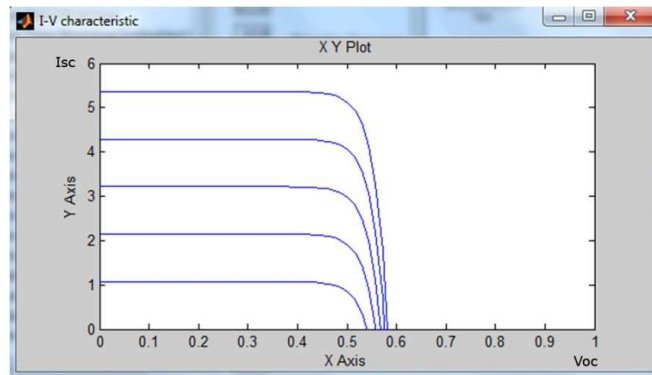


Fig. 8 Simulink I-V output

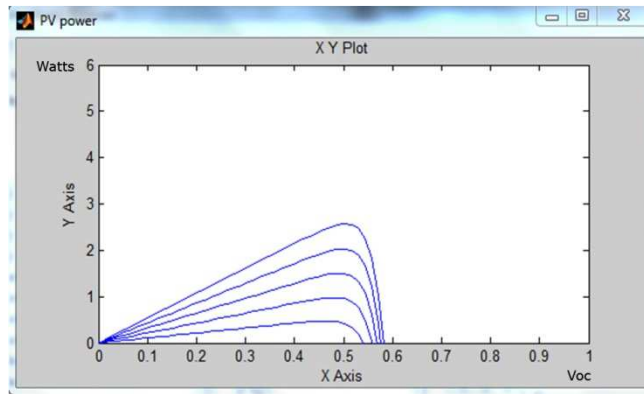


Fig. 9 Simulink Power output

Observe the striking similarity and the absence of any significant error between Fig.4 and Fig. 8 and between Fig. 5 and Fig 9. As a reference, the table below shows a typical data sheet for a solar cell. These specification sheets can be obtained from manufacturers.

Table 1

<b>SOLAREX MSX 60</b>	
<i>Characteristics</i>	<i>Specification</i>
Typical Peak Power (Pp)	60 W
Voltage @ Peak Power (Vpp)	17.1 V
Current @ Peak Power (Ipp)	3.5 A
Open Circuit Voltage (Voc)	21.1 V
Short Circuit Current (Isc)	3.8A
Temperature Coefficient of Voc	-73 mV/°C
Temperature Coefficient of Isc	3 mA/°C
NOCT	49°C
Approximate effect of Temperature on Power	-0.38 W/°C



Assessment- lectures and simulations of solar cells will be carried on during two weeks of a regular semester. The contact hours are three and a half hours per week. Explaining the basic principles of solar energy and solar cells will require a week (3 1/2 hours) and another week will be used for simulation purposes. Students will already have a working knowledge of Pspice and Matlab-Simulink.

The pre-test will be implemented at the end of the theoretical explanations. The post-test will be implemented at the end of the week of simulations. For pre and post tests a quiz format will be used with the same questions.

The comparison of pre and post tests will indicate the impact of simulations on learning outcomes. It will also identify what needs to be changed to improve the delivery of the material. This process will be carried on this semester in week 10 and 11 of the power electronics and photo-voltaic (PV) course.

Conclusions:-This paper demonstrates that the simulation by utilizing two different software packages is very close with a negligible error. This paper effectively simplifies the concept and focus on the results of the simulations. If this approach is successful, we intent to expand the material utilizing other software packages, include other topics such as the connection of solar cells in series, parallel, series-parallel arrays, explain and simulate the “shadow effect” and include other types of solar energy conversion.

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