EE362L Lab 2 Solar Power

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Abstract--Basic review of a Solar Photovoltaic System is presented. The efficiency of the panel is then calculated using voltage and current readings as well as compensating for solar orientation by using a known reference from a Solar PV radiometer.

I. Nomenclature

Solar, Photovoltaic, Efficiency, Insolation,

II. Introduction

The primary purpose of this lab is to become more familiar with Solar Power. Measuring the power output of a commercial solar photovoltaic panel by measuring its output in volts and amps and then constructing a power curve gives us a clear understanding of the basic operating conditions that affect it. This power curve can then be compared to a known value of solar radiation, and after taking into account the panel orientation, its efficiency can be calculated. A secondary purpose of this lab is for students to become more familiar with laboratory conditions where variable readings can be encountered. In this experiment on a partly cloudy day, measurements clearly indicate shifts when clouds briefly obscure the sun.

III. Experimental procedure and findings

Solar power is rapidly becoming more common as an alternate method for producing electricity. Photovoltaic, or PV, directly converts sunlight to electricity in a fairly simple manner. PV panels are made up of a large number of silicon diodes arranged in cells that convert light to electricity.[1,2]

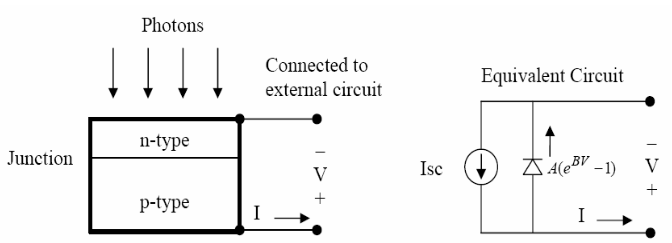

Figure 1. Equivalent Circuit for Solar Cell

Photons of light are absorbed by a simple P-N junction diode and create excess electron-hole pairs, which generate a small current. When a number of these are put in series, enough current is generated for the unit to become useful as a source of electricity. Since the available energy from sunlight is around 1kw/m2, even modest efficiencies (<25%) can generate significant amounts of electricity.

A. Calculating the power output from a panel

There are several Solar PV panels mounted on the roof of the ENS building, with voltage and current meters mounted in the lab area. The first part of the experiment was to determine the amount of power generated by a solar panel. I connected a variable load across the output terminals of a pair of Photowatt PW750-80 multi-crystalline panels rated at approximately 160 watts. The panels are connected in series since their maximum voltage is doubled to approximately 34.6V, but the current is constant at a maximum rated 4.6 amps. The load was varied from approximately zero to 50 ohms while current and voltage were recorded. Then, open circuit (I=0) and short circuit (V=0, I=I_{sc}) values were recorded.

A theoretical approximation of the current on a simple diode as a function of voltage and short-circuit current is given by the equation:

$$I = I_{SC} - A(e^{BV} - 1) \qquad (1)$$

where A, B are constants

The measurement data was entered into an Excel spreadsheet and the subroutine SOLVER was used to generate the best-fit for constants A and B by minimizing the sum of squared errors. Both actual and best-fit curves are shown in figure 2.

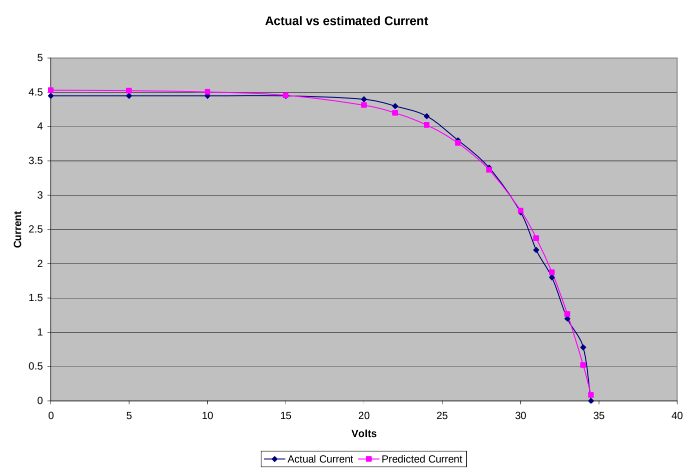

Figure 2. I-V Characteristics of Solar Panel

Since power is simply the product of voltage and current, the power can easily be calculated from the measured and best-fit data. The power output for both open circuit and short-circuit situations is zero since either voltage or current is zero. The power increases as the voltage is increased, reaching a peak value before decreasing as the resistance increases to the point where current drops off as shown in figure 3.

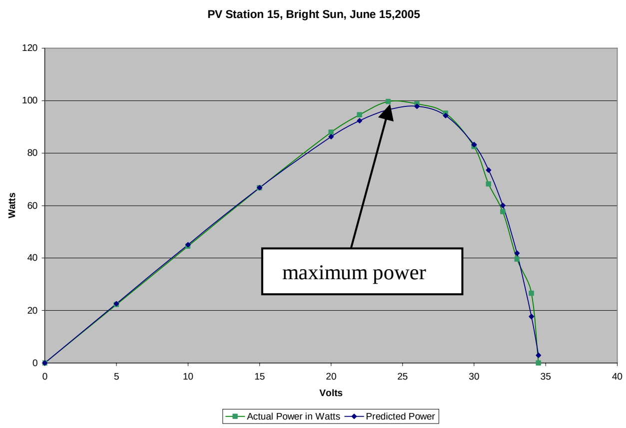

Figure 3 Voltage vs Power Generation for Solar Panel

The point of maximum power is the point where the load is matched to the solar panel's resistance at this level of insolation. Unfortunately, PV panels vary according to the ambient conditions, (light angle, ambient temperature, amount of insolation, etc), so commercial Solar PV system would operate most efficiently with systems that would automatically adjust their load to match. Also, to generate maximum power all day long, the panels would change orientation to track the sun. Unfortunately, tracking systems are relatively complicated mechanically, adding cost and complexity to the system.

B. Calculating efficiency

Efficiency is a key parameter for a solar PV system. Since PV generated electricity is fairly expensive (currently around $0.25 per kw-hr versus $0.125 for conventional generation), it is important that the solar panel operate at the same efficiency over time. The efficiency of a panel (or anything for that matter) is the power output over the incoming power. Although this is a relatively simple equation, calculating incoming power is slightly more complicated. The power generated by the sun is the amount of solar radiation per square meter. Calculating the amount of radiation on the angled surface of the PV panel is a geometric correction for the angle of incoming sunlight.

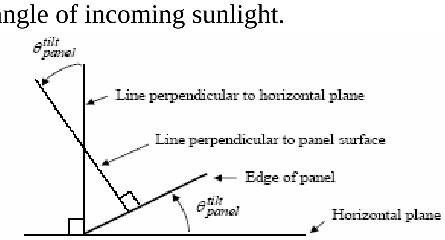

Figure 4 Simple geometric correction factor.

Since the panels are at a fixed angle and orientation, this value varies throughout the day as the sun passes overhead, and day-to-day throughout the year as the earth rotates around the sun.

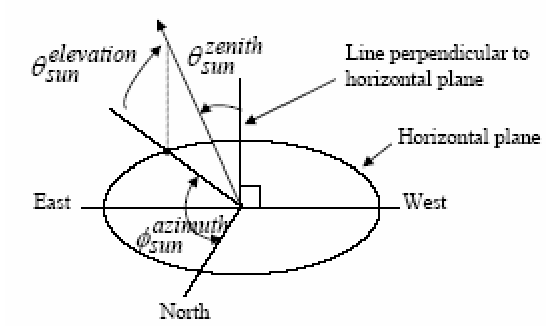

Figure 5 Geometric correction for position of sun.

Fortunately, for a given time and day, the position can be determined. Once the panel angle and orientation are known, the correction factor can be calculated from the angle of incidence between a unit vector perpendicular to the face of the panel and a unit vector from the sun to the panel. Or:

$$\cos(\beta_{incident}) = \mathbf{A}_{sun} \bullet \mathbf{A}_{panel} = A_{sun,x}A_{panel,x} + A_{sun,y}A_{panel,y} + A_{sun,z}A_{panel,z} \quad (2)$$

or, according to measured angles,

$$\cos(\beta_{incident}) = \cos(\theta_{sun}^{elevation})\cos(\phi_{sun})\sin(\theta_{panel}^{tilt})\cos(\phi_{panel}) + \cos(\theta_{sun}^{elevation})\sin(\phi_{sun})\sin(\theta_{panel}^{tilt})\sin(\phi_{panel}) + \sin(\theta_{sun}^{elevation})\cos(\theta_{panel}^{tilt})\,. \quad (3)$$

My measurements occurred at approximately 1:40 pm CST on June 20, 2005. The PV panel is mounted at 20 degrees elevation and an azimuth of 190 degrees, with a total area of 1.08 m^2. According to data generated from the Solar Website for that day[3], elevation was approximately 82 degrees and azimuth was approximately 166 degrees, yielding a correction factor (cos B incident) of approximately 0.97, which indicates that most of the incident solar radiation can be captured. This high factor also shows that the panels are set up correctly for the location so that the sun is directly overhead of the panels during most of the day as shown in fig 6.

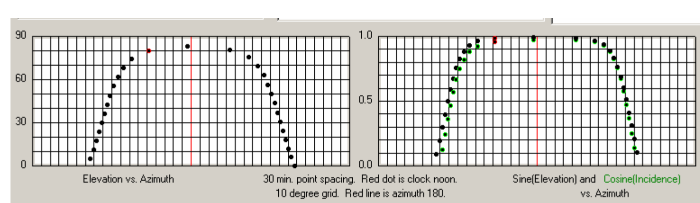

Figure 6 Solar Positions for June 20, 2005. [3]

Solar radiation is measured three ways: global horizontal (GH), diffuse horizontal (DH), and direct normal (DN). DN is the radiation direct from the sun. DH is indirect radiation, or radiation received by an object in a shadow. GH is the total of DN and DH. The normal units for solar radiation are

Watts/m^2.

Incident Solar Radiation is assumed to be all of the DH power plus the fraction of DN that is perpendicular to the panel surface. The incident power is simply the radiation per unit area times the panel area, which can be represented by the equation:

$$P_{incident} = \left[DH + \frac{(GH - DH)}{\cos(\theta_{sun}^{zenith})} \bullet \cos(\beta_{incident}) \right] \bullet A_{panel} \tag{4}$$

Solar radiation is measured by a rotating shadow band unit with a calibrated pyranometer to directly measure GH and DH and then calculate a value for DN.

Figure 7 clearly shows that even on a relatively sunny summer day in Austin, cloud conditions significantly impact the amount of solar radiation, causing significant variability (>20%!) in a short period. Ideally, the efficiency would be calculated on a day with stable solar radiation. Although the sensor readings are unstable for the date and time, the solar radiation values can be estimated at 760 W/m2 for GH and 225 W/m2 for DH. [3]

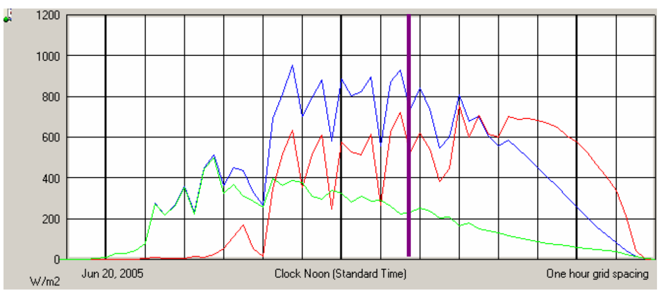

Figure 7 Solar Radiation Values for June 20, 2005. [3]

From the Solar Radiation data, incident power on the PV panels is calculated to be ~810 watts. Measured data from fig 3 showed actual maximum power to be 99.6 watts, for an overall panel efficiency of ~12.3%.

High temperatures reduce solar panel efficiency, and the ambient temperature on June 20 was almost 100 F!.

C. Conclusion

Solar PV is close to becoming an economically viable method for generating electricity. This experiment shows that the pair of Photowatt PW750-80 multi-crystalline cells operates at about 12.3% efficiency, generating about 100 watts of clean energy on a hot, partly cloudy day. The experimental calculations also show that the PV panels are angled appropriately for the sun, giving 97% or better coefficients for incident radiation. The panels are also oriented correctly to maximize the correction factor for maximum power throughout the day. Improvements in efficiency and reduced cost will lead to much greater acceptance in the future.

The experimental data also show that solar radiation is a highly variable source, which is one of the shortcomings of solar energy, along with its high cost. This variability is one of the hidden costs of distributed generation, since this drop in generation will need to be made up by the local utility for grid-connected systems. Further studies along this topic are needed.

IV. Appendix

Solar Energy experiment		Isc	4.532333379
20-Jun	1:40 PM	A	3.658E-03
	Station 15	B	2.059E-01

V	I	Ieqn	Ierror	Ierror square	Power, watts	Power Calc, watts
0	4.45	4.532333E+00	-8.23E-02	6.78E-03	0	0.0
5	4.45	4.525749E+00	-7.57E-02	5.74E-03	22.25	22.6
10	4.45	4.507316E+00	-5.73E-02	3.29E-03	44.5	45.1
15	4.45	4.455708E+00	-5.71E-03	3.26E-05	66.75	66.8
20	4.4	4.311218E+00	8.88E-02	7.88E-03	88	86.2
22	4.3	4.196686E+00	1.03E-01	1.07E-02	94.6	92.3
24	4.15	4.023794E+00	1.26E-01	1.59E-02	99.6	96.6
26	3.8	3.762805E+00	3.72E-02	1.38E-03	98.8	97.8
28	3.4	3.368830E+00	3.12E-02	9.72E-04	95.2	94.3
30	2.75	2.774106E+00	-2.41E-02	5.81E-04	82.5	83.2
31	2.2	2.371276E+00	-1.71E-01	2.93E-02	68.2	73.5
32	1.8	1.876343E+00	-7.63E-02	5.83E-03	57.6	60.0
33	1.2	1.268252E+00	-6.83E-02	4.66E-03	39.6	41.9
34	0.78	5.211281E-01	2.59E-01	6.70E-02	26.52	17.7
34.5	0	8.576188E-02	-8.58E-02	7.36E-03	0	3.0
		Sum of errors	-1.31E-03	1.67E-01		

Fig 8 Measurement Data for figures 2 and 3.

V. Acknowledgment

The author gratefully acknowledges the contributions of Dr Mack Grady, Virat Kapur and Yakub for their support and reference documents for this lab experiment.

Published Lab Procedures:

[1] Dr Mack Grady, "**EE362L, Power Electronics, Solar Power, I-V Characteristics",** Version June 6, 2005.

[2] Dr. Ewald Fuchs, "**Energy Conversion I,**" University of Colorado at Boulder.

Technical Data:

[3] Dr Mack Grady, "Texas Solar Radiation Database," University of Texas at Austin, http://www.ece.utexas.edu/~grady/Texas_Solar_Radiation_Data_Base.html

VI. Biographies

Clayton Stice (BSChE'1984, MSEE dec 2005,) was born in Chicago on Oct. 5, 1959. He graduated from the University of Texas and after a tour of duty in the Semiconductor Industry, is back in school. earning a masters degree in Electrical Engineering focused on Energy Systems.

His employment experience includes Advanced Micro Devices,, Therma-Wave, Inc, Sematech, and DuPont Photomasks. His special fields of interest included Thin Films and Yield Engineering..

During his career, Clayton discovered that his interests were in the development of large construction projects and returned to UT for an advanced degree that would enable him to undertake these types of challenges.