Experiment #1

Direct Energy Transfer

ECEA 5005 Photovoltaic Power Electronics Laboratory
University of Colorado, Boulder
Prof. Robert Erickson

The objectives of this experiment are:

- To characterize the photovoltaic panel used in this laboratory course, and to find numerical parameters of the equivalent circuit model for later use in the course
- To charge the deep-discharge lead-acid battery using the Direct Energy Transfer approach, and to evaluate the additional power that could be generated using Maximum Power Point Tracking

This experiment requires the following components and equipment from your parts kit:

- PV panel: 12 V, 10 W, Solarland SLP010-12U
- Absorbent Glass Mat (AGM) Lead-Acid Battery, 12 V, 3 A-hr, UPG UB1250
- Load resistors (2): 25 W, 30Ω, 280-CR25-30-RC
- Multimeters (2): DM-850 or equivalent

The SLP010-12U PV panel consists of 36 series-connected silicon cells, with no bypass diodes. The data sheet for this panel is linked to the course site. Silicon panels with 36 cells are traditionally designed for "12 V DC" systems; the open-circuit voltage V_{oc} and maximum power-point voltage V_{mp} both are greater than the maximum battery voltage of 13-15 V.

The UB1250 deep-discharge lead-acid battery has a nominal voltage of 12 V and a capacity of 3 A-hr; the data sheet for this battery also is linked to the course site. This battery has six series-connected battery cells each with a nominal voltage of approximately 2 V. It is traditional to define the battery capacity C as the current that discharges the battery in one hour; the battery then has a charge capacity of $C \cdot$ (1hr) Ampere-hours.

The *state of charge* (SOC) of a battery is the residual capacity of a partially discharged battery, usually expressed as a percent of full charge. The state of charge is approximately proportional to the open-circuit equilibrium voltage, and a plot of this is included on the data sheet. It is important to avoid discharging the battery below the voltage corresponding to 0% SOC: deeply discharging a lead-acid battery irreversably reduces its capacity and life. Also, it is important to avoid overcharging the battery above the open-circuit voltage corresponding to 100% SOC: overcharging causes secondary chemical reactions such as electrolysis of the water, leading to outgassing that can damage the battery. With current flowing, the battery terminal voltage can differ from the equilibrium open-circuit voltage by the voltage drop across an equivalent series resistance (ESR); the origins and behavior of battery ESR are discussed in more detail later in this course.

Two 30Ω 25 W power resistors are included in the kit for loading your PV panel and/or dc-dc converter. These resistors can be connected alone or in series or parallel to load your panel as necessary.

In this experiment, one multimeter is used to measure the voltage of the PV panel, and a second multimeter is used to measure current. Note that when a multimeter operates in ammeter mode, it is nearly a short circuit, and it is intended to be connected in series (*not in parallel*) with the device whose current is being measured. If you connect your ammeter in parallel with the battery, a very large current will flow through the meter terminals that will blow the internal ammeter fuse. The ammeter then will behave as an open circuit until its fuse is replaced.

Experimental Procedure

It is necessary to perform this experiment on a sunny day, with the PV panel in full sun. If operated inside, the PV panel will produce negligible power. If the weather is bad, do your best to capture as much sun energy as you can.

1. First, use a multimeter as a voltmeter to measure the open-circuit voltage of your battery. If this voltage is greater than approximately 13.2 V then the battery SOC is 100% or even greater, and it would be best to avoid overcharging by discharge the battery somewhat before performing the charging discussed below. More likely, the open circuit voltage will be lower; when the equilibrium open-circuit battery terminal voltage is below approximately 12 V then the battery SOC is at 0% and charging is required.

Record the battery open-circuit voltage V_{oc}, and estimate the battery SOC assuming that SOC is linearly proportional to equilibrium V_{oc}.

2. The PV panel electrical output terminals can be accessed by unscrewing the cover of the junction box on the back side of the panel. This step must be done outside in the sun. Orient your PV panel so that it is facing the sun, and work quickly. Connect one multimeter to measure the PV panel output voltage V_{pv}, and connect another multimeter to measure PV panel output current I_{pv}. Take experimental readings of six operating points:

(a) Open circuit, with $I_{pv} = 0$

(b) Short circuit, with $V_{pv} = 0$

(c) Loaded, with a 30Ω resistor connected to the PV panel

(d) Loaded, with two 30Ω resistors connected in parallel and to the PV panel

(e) Loaded, with two 30Ω resistors connected in series and to the PV panel

(f) Loaded, with the PV panel connected to charge the battery (be careful to connect the positive terminal of the PV panel to the positive terminal of the battery for this part!). This charging configuration is called *direct energy transfer*.

Note that the panel i–v characteristic changes when any of the following occur: the panel temperature changes (the diode voltage decreases as its temperature increases), the orientation of the panel with respect to the sun changes, or the atmospheric conditions change.

3. With your PV panel connected to the battery as in step 2(f) above, use a small piece of paper or index card to shade two cells of the PV panel, with the remaining cells in full sun. Again measure I_{pv} and V_{pv}.

Calculations

4. In your report, include your measured battery voltage from step 1 above. Calculate the estimated battery SOC for this step by linearly interpolating the battery open circuit voltage vs. residual battery capacity.

5. In your report, include a table of the experimental data for the six operating points of step 2 above. Plot the measured I_{pv} vs. V_{pv} characteristic for your panel. Also plot the P_{pv} vs. V_{pv} characteristic, where $P_{pv} = I_{pv}V_{pv}$. Compare your measured data with the data sheet:

(a) How do your measured V_{oc} and I_{sc} compare with the data sheet specifications?

(b) How does your measured I_{pv} vs. V_{pv} plot compare with the typical plot given in the data sheet?

(c) What maximum power did you measure? How does this compare with the date sheet specifications?

(d) Compute the area of the PV panel using the outside dimensions of the frame as given in the data sheet, and express your answer in m^2. Using the data sheet specified I_{mp} and V_{mp}, compute the theoretical panel efficiency when the solar irradiance is 1000W/m^2. Also compute the panel efficiency using the maximum power that you measured.

(e) What happens to the battery charging current when two cells of the PV panel are shaded (as in step 3 above)?

6. In your report, include the power that charged the battery using direct energy transfer. Also estimate the power that could charge the battery with ideal *maximum power point* charging:suppose a dc-dc converter with 100% efficiency were connected between the PV panel and the battery, and operated at a duty cycle such that the PV panel operates at its maximum power point and the battery voltage is the value measured in step 2(f). Under these conditions, how much larger would the battery charging current and power be?

Equivalent Circuit Modeling of PV Panel

The standard electrical equivalent circuit model for a photovoltaic cell is illustrated in Fig. 1. The current source I_0 models the photo-generated current, and is approximately proportional to the solar irradiatiance: $I_0 = k_i(irradiance)$. The diode exhibits an exponential $I_{cell} - V_{cell}$ characteristic, according to the conventional diode equation $I_D = I_{D0}(e^{\lambda V_D} - 1)$ with $\lambda = q/kT = (26mV)^{-1}$. Resistor R_p models current due to leakage and defects, and is usually of large value. Resistor R_s models bulk and contact resistance, and has relatively small value.

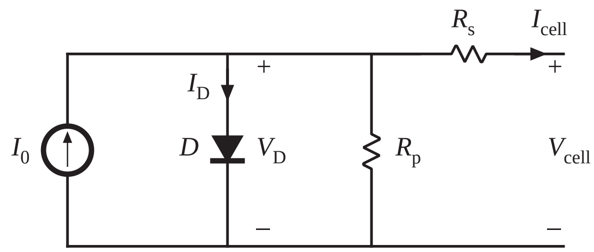

Figure 1 Basic equivalent circuit model of a PV cell.

7. Find values of k_i, I_{D0}, R_p, and R_s, such that the model of Fig. 1 predicts the curve you measured in step 4 above. You may assume that all cells are identical, so that the total panel voltage V_{pv} is equal to 36 times the voltage of one cell V_{cell}. Plot the $I_{pv} - V_{pv}$ characteristic predicted by your model, and overlay your experimental data points. It will be necessary to manually iterate to find parameter values that cause your plot to agree with your experimental data. If you took your data on a nice sunny day, and if you were careful to point your panel directly at the Sun, then your solar irradiance should have been close to 1000W/m^2. Compare the model-predicted open-circuit voltage, short-circuit current, and maximum power point voltage and current, with your measured data. You should use LTspice to assist with this part. In your report, document your cell equivalent circuit model including numerical values for all parameters. Include your $I_{pv} - V_{pv}$ plot, with experimental data point overlayed. Discuss how well the data sheet curve agrees with your model.

8. Assume that the current source I_0 in your equivalent circuit model is directly proportional to solar irradiance. Use your model to plot the predicted PV panel $I_{pv} - V_{pv}$ characteristics when all cells are uniformly illuminated at 250, 500, 750, and 1000 W/m^2. Include this plot in your report, along with a listing of the LTspice circuit input (schematic or netlist) that produced this plot.

A Preliminary Converter Specification

In Experiment 3, you will design and construct a dc-dc converter to interface the PV panel to the battery. This converter should be capable of operating the PV panel at its maximum power point, and also to operate the PV panel over the remainder of its *i*–*v* characteristic.

9. Draft some preliminary specifications for this dc-dc converter. For requirements (a)–(d) below, estimate numerical values and provide a short (a few words) basis or justification for your choice.

(a) Converter input: voltage and current range

(b) Converter output: voltage and current range

(c) Converter switching frequency

(d) Converter peak efficiency, at V_{in} = 17 V, V_{out} = 12 V, and $0 \le P_{in} \le 10$ W

(e) Reverse power flow (from battery into PV panel) is prevented

Experiment 1 Grading Rubric

PV Characteristics and Direct Energy Transfer

1. Battery V_{oc} recorded, and battery state of charge estimated (6 points)

2. PV panel V_{oc} measured and value recorded (2 points)

3. PV panel I_{sc} measured and value recorded (2 points)

4. Collection of PV panel I_{pv} vs.V_{pv} data at six points: open circuit, short circuit, with resistive loads of $15\Omega, 30\Omega, 60\Omega$, and with direct connection to battery. Full credit if all data is present and appears correct. (10 points)

5. Plot of PV panel experimental data: I_{pv} vs. V_{pv} and P_{pv} vs. V_{pv}. Full credit if all data is plotted correctly. (10 points)

6. Battery charging current when PV panel is partially shaded. Include a sentence explaining result. (5 points)

7. Comparison of measured plots vs. data sheet, including I_{sc}, V_{oc}, and P_{mp}. Briefly discuss potential reasons for any discrepancies. (5 points)

8. Compute the PV panel efficiency, based on your measured data and the panel outside dimensions listed on the datasheet. (5 points)

9. Estimate the increase in power with which the battery could be charge if maximum power point tracking were used, rather than the direct energy transfer approach used in this experiment. (5 points)

PV Panel Equivalent Circuit Model

10. Sketch the equivalent circuit model you developed for your PV panel, and give numerical values for the four cell parameters: gain k_i of current source modeling solar irradiance, diode I_{D0}, shunt resistance R_p, series resistance R_s. (10 points)

11. Provide a screen capture of your simulation model (LTspice or MATLAB) and its I_{pv} vs. V_{pv} plot for your PV panel at a solar irradiance of $1000\mathrm{W/m^2}$. (10 points)

12. What values of I_{sc}, V_{oc}, and P_{mp} does your simulation model predict? Compare with the data sheet specifications, and briefly discuss any discrepancies. (10 points)

13. Using your simulation model, predict the I_{pv} vs. V_{pv} characteristics of your panel for solar irradiances of $250\,\mathrm{W/m^2}$, $500\,\mathrm{W/m^2}$, $750\,\mathrm{W/m^2}$, and $1000\,\mathrm{W/m^2}$. Overlay these plots on the same graph. (10 points)

Preliminary Converter Specification

14. Specify converter input range: voltage and current (2 points)

15. Specify converter output range: voltage and current (2 points)

16. Preliminary choice of converter switching frequency (2 points)

17. Preliminary estimate of converter peak efficiency for $V_{pv} = 17$V, $V_{batt} = 12$V, and $0 \leq P_{pv} \leq 10$W. (2 points)

18. Brief explanation of approach for preventing reverse power flow (from battery to PV panel). (2 points)