Lab3: PV MPPT

Photovoltaic cells are a great source of renewable energy. With the sun directly overhead, there is about 1kW of solar energy (energetic photons) per square meter of area. A photovoltaic panel converts this solar energy into electricity. A photovoltaic controller optimizes the operating point of a panel, or string of panels, for peak efficiency and converts the raw electrical energy out of the panel into a useful level.

In this lab you will build a photovoltaic controller that controls a single panel and optimizes its operating point driving a resistive load.

The goals of this lab are to teach:

1. The basic electrical characteristics of photovoltaic cells and panels.
2. How to use dithering and a gradient search to optimize a convex function.
3. The details of the *boost* converter as it is applied to converter a lower voltage (from the solar panel) to a higher voltage (to the load).

Assigned: October 9, 2017

Due: Week of October 16, 2017

Part 1

Photovoltaic Panel

For our laboratory we will be using a CS6P-235PX solar panel manufactured by Canadian Solar. The I-V curves for this panel are shown in Figure 1 and the key parameter for the panel are shown in Table 1. At full irradiance, the panel has a short-circuit current (the current that flows if you short its leads together) of $I_{SC} = 8.46$A. And this current falls off linearly as irradiance is reduced. The panel has an open circuit voltage of (the voltage that appears across its terminals with no current flowing) of $V_{OC} = 36.9$V. The open circuit voltage is reduced slightly as irradiance is reduced but is a strong function of temperature.

Symbol	Value	Units	Description
N_C	60		Number of Cells
V_{OC}	36.9	V	Open Circuit Voltage
I_{SC}	8.46	A	Short-Circuit Current
V_{MP}	29.8	V	Maximum Power Voltage
I_{MP}	7.90	A	Maximum Power Current
eta	14.6	%	Efficiency

Table 1: Key parameters of the CS6P-235PX solar panel at 1kW/m^2 and 25°C

The current is initially very flat, holding relatively steady as voltage is increased until about 30V. At that point the current drops exponentially with voltage. The peak power point, the point where the power (the product of voltage and current) is at a maximum at the knee of this curve.

Part 1 continued on next page. . .

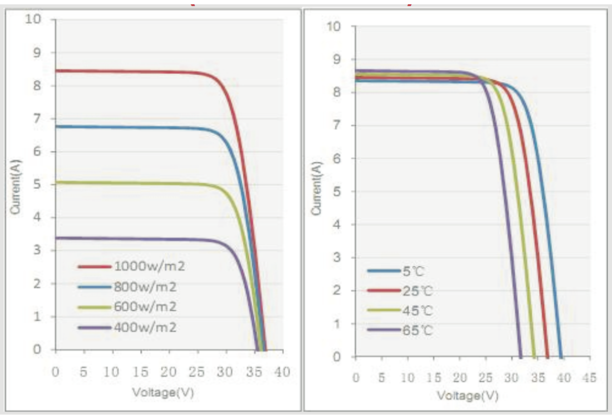

Figure 1: IV curves for the CS6P-235 235W Solar Panel.

Figure 2 shows a circuit model of a single photovoltaic cell. We model the cell as a current source — that represents the photocurrent generated by energetic photons — in parallel with two diodes. The diodes have different characteristics, one is nearly ideal with an emissivity constant $n = 1$ and $I_{\text{Sat}} = 3 \times 10^{10}$ while the other represents losses due to recombination and other effects and hence has an emissivity constant of $n = 3$ and $I_{\text{Sat}} = 5 \times 10^4$. The shunt resistor R_{SH} sets the slope of the horizontal part of the current curve at low voltages. The series resistor R_S sets the slope of the vertical part of the current curve at low currents.

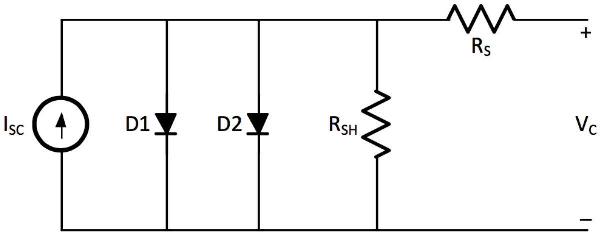

Figure 2: Model of a single photovoltaic cell.

Power Path

Figure 3 shows the power path of the PV controller, a simple boost converter. The PV panel provides energy at its operating voltage V_{PV} and current I_{PV} , which is sensed across resistor R_S. Input capacitor C_i stores this energy to smooth the inductor ripple current. Current in inductor L_1 ramps up when MOSFET M_1 is on and ramps down — transferring its energy to the higher load voltage V_L — when M_2 is on. Output capacitor C_O smooths the output load current.

As derived before, the duty factor D of M_1 determines the voltage ratio.

$$\frac{V_L}{V_{PV}} = \frac{1}{1 - D} \tag{1}$$

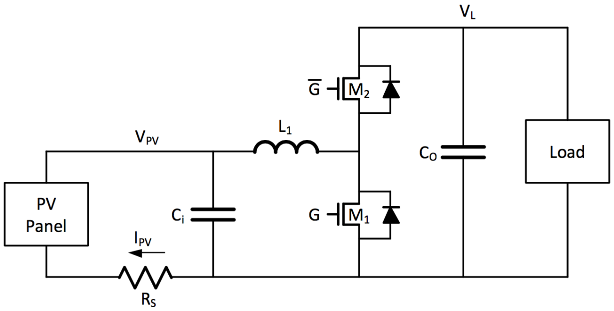

Figure 3: Power Path of the PV Controller.

Controller

To find the peak-power point of the photovoltaic panel, our controller uses a technique called *gradient search* or *hillclimbing*. Starting from the current operating point, we vary the operating voltage of the PV panel slightly (this is called *dithering*) and measure the power at the new operating point. If the power goes up, we accept the new operating point. If the power goes down, we go back to our old operating point and try searching in the other direction.

While we could search by varying V_{PV} or I_{PV} and then, using a layered controller, determine the duty factor D that corresponds to the setpoint, it is simpler to remove the indirection and perform gradient search directly on duty factor.

Our controller is summarized in the pseudo-code of Listing 1. Starting from an initial point, the loop repeatedly dithers from the current operating point, waits for the system to stabilize, and then remeasures power. If the new power is an improvement, the new operating point is accepted and the search continues. Otherwise the controller returns to the old operating point and reverses the direction of search.

Listing 1: Pseudo-code for MPPT controller.

```
df = INITIAL_DUTY_FACTOR ;
run_until_stable() ;
power = measure_power() ;
delta_df = DELTA_DF ;
old_df = df ;
old_power = power ;
do {
  df = df + delta_df ;
  run_until_stable() ;
  power = measure_power() ;
  if(power > old_power) {
    old_power = power ;
    old_df = df ;
  } else {
df = old_df ;
    delta_df = - delta_df ;
  }
}
```

Part 2

The Lab

1. Wire up the power path of Figure 3 and control it using a 100kHz PWM signal from the processor module. Write the embedded code to perform the maximum-power point tracking.
2. Test your prototype PV controller using a lab power supply set for 30V maximum voltage and 3A maximum current to simulate a PV panel (albeit with a rather square I-V curve. Your maximum-power point tracker should find the pulse width needed to stay at this maximum power point.
3. Test your prototype PV controller using an actual solar panel. Verify that it finds a new maximum-power point when you shade half of your panel with a piece of cardboard.
4. (Optional) Measure the efficiency of your PV controller by placing energy meters before and after the controller.

Extensions

Inverter: Modify your PV controller to include an inverting output stage to interface with a power line. The boost stage of Figure 3 should be modified to produce an intermediate voltage that is larger than the maximum AC voltage (170V for 110V AC and 340V for 220V AC). A full-bridge stage should then be added to synthesize a sine wave via pulse-width modulation. An LC output filter is needed to filter out the PWM frequency noise.

Panel Balancing: If two PV panels (or two PV cells) connected in a string are not identical or do not have identical irradiance, it will not be possible to simultaneously find the maximum-power point for both. The current i_{PV} which is common to all of the panels in a string will be a compromise between the maximum-power current of the two panels.

Using our Matlab model for a solar panel, quantify the amount of power lost when two panels must operate at the same current point when one has an full irradiance ($1000\mathrm{W/m^2}$) and the other has half irradiance ($500\mathrm{W/m^2}$) compared to the power when both are operated at their individual maximum-power points.

The current of each panel (or cell) in a string can be made individually adjustable by using a pulse-width-modulated inductor to losslessly bypass current around panels requiring a lower current. Design such a panel bypass circuit and simulate it in SPICE on a two-panel configuration.

(Optional) Implement your circuit and demonstrate it on a real two panel configuration with one panel half shaded.

Variable-Step Gradient Search: Our gradient-search algorithm has a fixed step size. This causes it to take a long time to track a large transient and at the same time results in a fairly large dithering region once we are converged on the maximum-power point. Develop a better search algorithm that varies the step size for faster tracking of transients and smaller dithering intervals when converged.

Soft Switching: Our PV controller power path performs hard switching, resulting in significant switching losses. By switching our MOSFETs only when the current through them is zero (zero-current switching

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or ZCS), or the voltage across them is zero (zero-voltage switching or ZVS), or both, we can reduce the switching losses to zero.

Design a power path that uses soft switching to eliminate switching losses and simulate this power path using SPICE. Measure the total losses — switching, MOSFET conduction, and inductor conduction and core losses — for both the original configuration and your new design.

(Optional) Implement your design and demonstrate it operating with a PV panel. Measure its efficiency using an energy meter before and after the PV controller.

Stability Analysis: We use a 10μF film capacitor for Ci because it reduces voltage ripple due to the inductor current ripple to acceptable levels. It turns out that if this capacitor is made very large, say 1mF, the PV controller will oscillate. Develop a model of the PV controller that allows you to study its stability. Using your model, predict the value of capacitance that causes the controller to oscillate. Develop a strategy to stabilize the controller when using a large capacitor.

Signoffs

1. Demonstrate functioning MPPT controller with lab power supply.
2. Demonstrate functioning MPPT controller with solar panel.