Experiment 2

Solar Battery Charger Modeling and Testing

ECE 481: Power Electronics

Fall 2017

The objectives of this experiment are:

- To test and understand steady-state behavior of a GaN-based converter
- To validate analytical loss models of a PWM converter
- To examine techniques for Maximum Power Point Tracking (MPPT)

Modifications on 11/6/17 are shown in red.

I. Background

As analyzed in experiment 1, PV output power has significant dependence on loading. In order to extract maximum power from the panel, the load presented to the panel needs to be appropriately conditioned. Fig. 1 reviews the general results from experiment 1. On the PV panel *i-v* characteristic, maximum power occurs at a single point, the Maximum Power Point (MPP). Operation at this point can be achieved by loading the panel with a constant current, $I_{panel} = I_{MPP}$, a constant voltage, $V_{panel} = V_{MPP}$, or a resistance $R_{load} = R_{MPP}$.
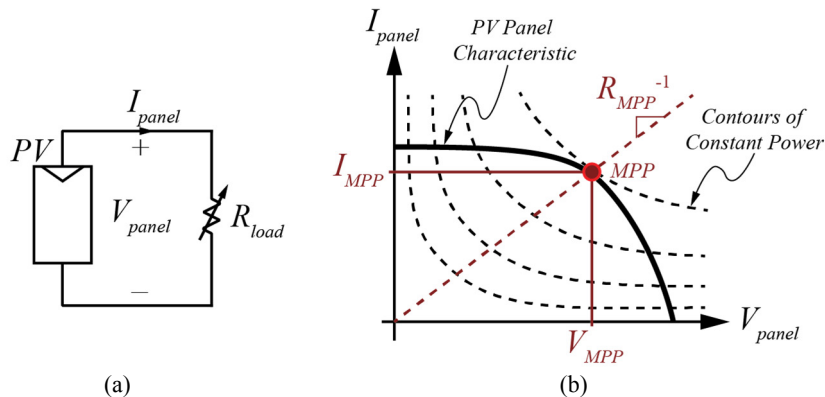

<div align="center">(a)   (b)</div>

Fig. 1: PV panel model (a) and *i-v* characteristic (b)

However, each of these values (I_{MPP}, V_{MPP}, R_{MPP}) vary with solar irradiance, either slightly or significantly. If a PV panel is connected directly to a battery, it is unlikely to yield maximum power. Instead, power electronics are often used between the PV panel and load to decouple the load behavior from the PV panel and allow the panel to operate at its maximum power point.

Synchronous Buck Converter

In this experiment, we will use a synchronous buck converter to perform Maximum Power Point Tracking (MPPT). The synchronous buck converter differs from the conventional transistor-diode converter in that the diode has been replaced by a second transistor. Recall from lecture that the diode is a single-quadrant switch, and the FET is a current-bidirectional two-quadrant switch, so either can be used to achieve buck converter operation. The synchronous buck converter is often used in applications with low voltage and high current, where the conduction losses of a FET can significantly improve on those of a diode.

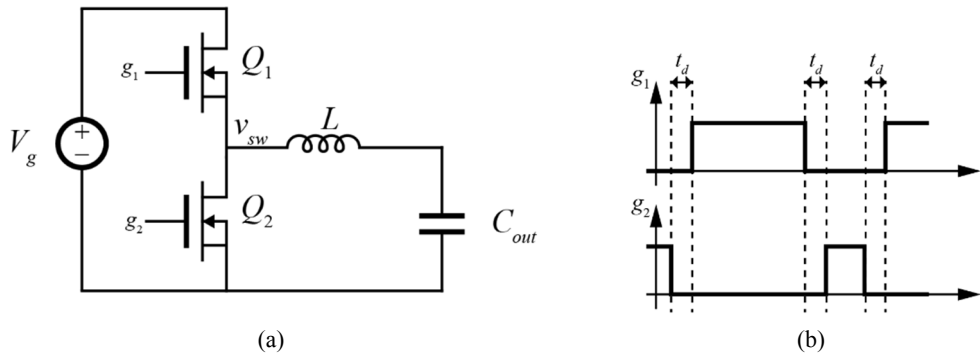(a)   (b)

Fig. 2: Synchronous buck converter (a) and gate drive signals (b).

Because both switches are now current-bidirectional, DCM will not natively occur in the synchronous buck converter; the converter will remain in CCM even at very low output power. However, because both switches are actively controlled (by their respective V_{gs} signals), it is possible to have both on simultaneously. If this happens, the two FETs will short out the input voltage source, and cause a very large spike in current. This phenomenon, known as cross-conduction, will result in significant power loss and, potentially, device failure. As such, it is to be avoided. To guard against this situation, the synchronous buck converter requires gate drive signals with dead time t_d, as shown in Fig. 2. The dead time is a short interval where neither FET is on, to allow some margin between their conduction intervals to ensure no cross-conduction occurs. During the dead time, neither FET's channel is on, but the body diodes may still conduct if the inductor current is non-zero.

Wide Bandgap Semiconductors

The buck converter used in this experiment employs two Gallium Nitride Field Effect Transistors (GaNFETs). These transistors use GaN as their substrate, as opposed to traditional silicon FETs. At the material level, GaN has favorable properties that allow for transistors to be implemented with lower switching loss, lower on-resistance, and smaller physical size than feasible in silicon. However, due to being a relatively new technology, many GaN devices are less robust than their silicon counterparts, and may easily be destroyed if operated outside of their rated voltages and currents. Be sure to exercise caution throughout the experiment to prevent accidental failures of the devices.

Additionally, the devices used in this experiment are implemented with a different structure than traditional silicon power MOSFETs. They are lateral, rather than vertical, power devices, and use a very high conductivity interface between two materials for conduction, rather than doped majority carriers. More information on GaNFETs can be found here:

http://epc-co.com/epc/Portals/0/epc/documents/papers/Gallium%20Nitride%20GaN%20Technology%20Overview.pdf

One important characteristic to note, is that these devices contain no body diode. They do, however, have a reverse conduction mechanism that will turn the channel of the device on, weakly, if the drain-to-source voltage goes below zero. Functionally, the behavior is similar to that of a body diode, but (1) it has larger conduction loss than a body diode and (2) it will not exhibit any reverse recovery.

II.   Procedure

In this experiment, you will construct and test a solar battery charger using a synchronous buck converter. The system schematic is given in Fig. 3. We will again use a current-limited DC supply to emulate solar irradiance on the solar panel. The buck converter will then be used to interface the panel to a battery, while extracting maximum power from the panel. An electronic load will emulate a V_{bat} = 8 V; however, we will

Incorporating a battery into the system has multiple advantages. First, battery storage allows the system maintain an output voltage even when the photocurrent is low (or zero) in the panel. Second, the battery allows the panel to generate maximum power. If no battery storage is used, the duty cycle of the converter must be set to regulate the output voltage. In this way, the load dictates the duty cycle and the output power of the converter, and therefore the input power of the converter (if $\eta \approx 1$). This prevents the converter from operating at the MPP of the panel, and generating the maximum energy.
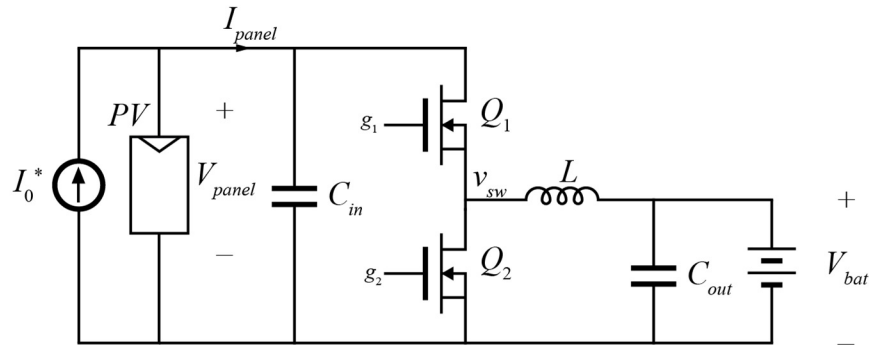

Fig. 3: Solar battery charger to be tested in Experiment 2.

The components used in this system are as follows

Table I: Buck Converter Components

Component	Part Number	Datasheet
Power Stage	LMG5200	http://www.ti.com/product/LMG5200
Inductor	2107-H-RC	http://www.bourns.com/pdfs/2100_series.pdf
Capacitors	R60DR52205040J	https://content.kemet.com/datasheets/KEM_F3103_R60.pdf
PWM	LTC6992-1	http://cds.linear.com/docs/en/datasheet/69921234fc.pdf

The power stage consists of two GaNFETs and all necessary gate driver circuitry to generate the gate drive signals in Fig. 2(b).

    a. PV panel Operation

Using your model from Experiment 1, determine the duty cycle at which the converter should operate to extract maximum power. Note that this duty cycle may vary with the photocurrent I_0^*. **Generate a graph** of the maximum power vs photocurrent, and, on the same plot, the optimal duty cycle the buck converter must operate at to ensure the maximum power is supplied to the 8 V load. Also, solve for the output current supplied to the 8V battery at this operating point.

Note: you may use the ideal, averaged model of the buck converter in determining the duty cycle

In your report **comment on** the variation in duty cycle with photocurrent. How would the duty cycle change if the load were instead a fixed resistance (Rather than fixed V_{bat})?

    b. Converter Testing

The power stage demo board used in this experiment is shown in Fig. 4, with the experimental setup in Fig. 5. The LMG5200 contains the two power GaNFETs, and all associated gate driver circuitry. The LTC6992-1 is an PWM oscillator, which is controlled by the slide potentiometer R13. Be careful not to

slide the potentiometer all the way to the top, as a duty cycle $D = 1$ will cause irregular operation of the gate driver.

To begin, test the minimum photocurrent that was characterized in Experiment 1. Assemble the circuit as follows.

1. Attach oscilloscope probes to the input voltage, switched-node voltage, output voltage, and to the top-right pin of the "Mode Select" header (this last probe will measure the PWM signal).
2. Using a separate power supply from the PV panel photocurrent emulator, apply 5V between the VCC and GND pins of the board.
3. The PWM input signal is generated by the LTC6992. An analog voltage signal between ~0.2V and 0.8V on the MOD pin determines the duty cycle. This analog voltage is supplied by a potentiometer from V_{cc}. By adjusting the slide potentiometer, set the duty cycle to your prediction from part a. You should be able to see the PWM on the probe connected to the top-right pin of the "Mode Select" header.
4. Connect two multimeters to measure current and voltage as shown in red in Fig. 5
5. Connect the electronic load at the output. Set it to constant voltage mode, set the current value to zero, and turn it on.
6. Once the load is connected and on, and the PWM modulator is working, connect the panel and photocurrent emulator supply (as in experiment 1) to the circuit, with the photocurrent supply set to 0 V and 0 A. Slowly increase the current limit to the photocurrent operating point you are testing, then increase the voltage limit until the power supply goes into CC mode.
7. Now, set the electronic load current your prediction from part (a) for this photocurrent. If the values for D and I_{out} are correct, the output voltage should go to 8 V. If not, you may need to adjust the operating point. Using the slider, you can adjust D; you should see that there is a maximum output voltage possible, and away from this point the voltage drops whether D is increasing or decreasing. If you cannot achieve 8 V output even as you adjust the duty cycle, you will need to decrease the electronic load current.
8. Record the photocurrent, input voltage and current (from the multimeters) and output voltage and current (from the electronic load). Capture waveforms on the oscilloscope that show two full periods of the voltage waveforms listed in step 1. **Include these waveforms** in your report, and comment on any details of them.
9. Repeat steps 1-8 for at least five points spanning the range of photocurrent from 0 to 0.77A. You may need to alter the duty cycle at each operating point to make sure maximum power is extracted from the panel.
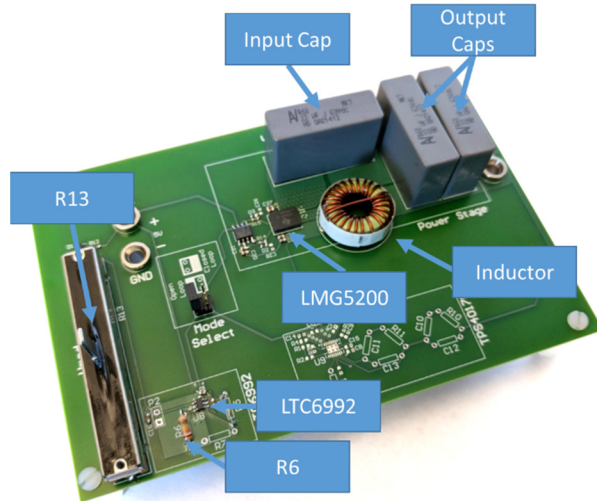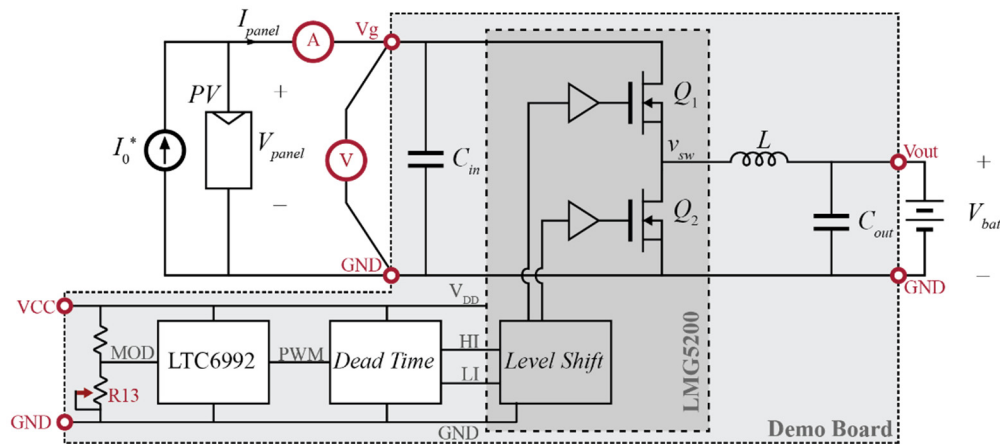
Fig. 4: Demo board used in Experiment 2

Fig. 5: Experimental setup for testing solar battery charger. The gray box denoted circuitry on-board the EPC9003 evaluation board.

Note that the power stage is limited to 5 A. Though this is significantly higher than the maximum current of the PV panel, it is possible to exceed this limit during a transient. Always begin switching first, then slowly bring up the input power from zero. Do not bring the input voltage up, then begin switching – doing so results in a transient condition which may cause a device failure.

    c.   Measurement Analysis

Generate a plot of measured efficiency vs. photocurrent.

Generate a plot of input power vs photocurrent, using your measured results. Compare this plot to the one generated in part a. Again comment on any differences.

In a maximum power point tracking system, there are two efficiencies we are concerned with. First, as with any power converter, we want to have high conversion efficiency,

$$\eta_{conv} = \frac{P_{out}}{P_{in}}.$$

Additionally, we want to have high tracking efficiency,

$$\eta_{track} = \frac{P_{in}}{P_{MPP}},$$

which measures how well the converter control tracks the maximum power point. Even if the converter is 100% efficient, if the operating point is far from the MPP, the system will extract lower power. In your report, include a table of the form of Table II, with your measured data. Also include waveforms measured at each operating point. Comment on the performance of your system, and the measured waveforms. Do the waveforms match your expected shape? What could be the cause of any discrepancy?

Table II: Measurement Results

Photocurrent	Duty Cycle	V_{in}	I_{in}	V_{out}	I_{out}	η_{conv}	η_{track}
0.1 A	23.3%	18 V	0.09A	8 V	0.3A	78%	80%
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

d. Converter Modeling

Develop an analytical loss model of the converter, including loss elements for all devices. Refer to the datasheets of the individual components for the values of parasitics (e.g. on-resistance of FETs, DCR of inductors). Using the results from (a), **generate a plot** of efficiency-vs-photocurrent for the converter when operated at the maximum power for any given photocurrent. Compare this model with your measured results from part c. **Comment** on any discrepancies, including your thoughts on why the curves differ.

Next, generate an LTspice simulation model of your test. Starter files for the simulation are available on the course website, which contain models for the LMG5200. Combine this with your PV panel model from experiment 1. Adjusting the duty cycle and photocurrent in simulation, compare simulation efficiency and waveforms to your experiments and your analytical model.

Note: In simulation, be sure to let the converter reach steady-state before assessing the efficiency. This may require adjusting the simulation time. Also, when measuring efficiency, measure both input and output power in a transient simulation. CTRL+click on the waveform to see it's average. Make sure your window is set to have (any) integer number complete periods of steady-state before viewing the average.

Generate a plot of efficiency-vs-photocurrent for the simulation. **Comment** on any discrepancies between this, your analytical model, and your measured results, including your thoughts on why the curves differ.

e. Extra Credit (20% of experiment grade)

The switching frequency of the converter is set by the resistor R6. Nominally, R6 = 100 kΩ, which sets the switching frequency to 500 kHz (N_{DIV} = 1). By reading the datasheet of the LTC6992, determine how to adjust R6 to change the switching frequency f_s. Using your converter model from part (d), determine the maximum switching frequency $f_{s,max}$ possible such that $\eta > 90\%$ when at the MPP with a photocurrent of 0.5A. Purchase this resistor from the parts store and solder it in place of R6, then test the converter at this operating point and confirm $\eta \approx 90\%$. Include in your report the value of R6, the details of your modeling and solution for $f_{s,max}$, oscilloscope waveforms of your converter operating at this point, and your measured input and output voltage and current.