Experiment 3

Buck Converter Small Signal Modeling

ECE 481: Power Electronics

The objectives of this experiment are:

- To model the small-signal dynamics of a PWM converter
- To experimentally test small-signal transfer functions
- To examine the impact of nonidealities on converter transfer functions

I. Background

In Experiment 2, we characterized a buck converter used for maximum power tracking of the solar panel. This converter interfaced the panel to an 8V battery, used to decouple the power from the panel (which is to be maximized) from the power to the load (which is dictated by the load i.e. out of our control). To complete the solar USB charger, we need an additional converter which interfaces the 8V battery to the 5V USB loads. This is shown in Fig. 1.

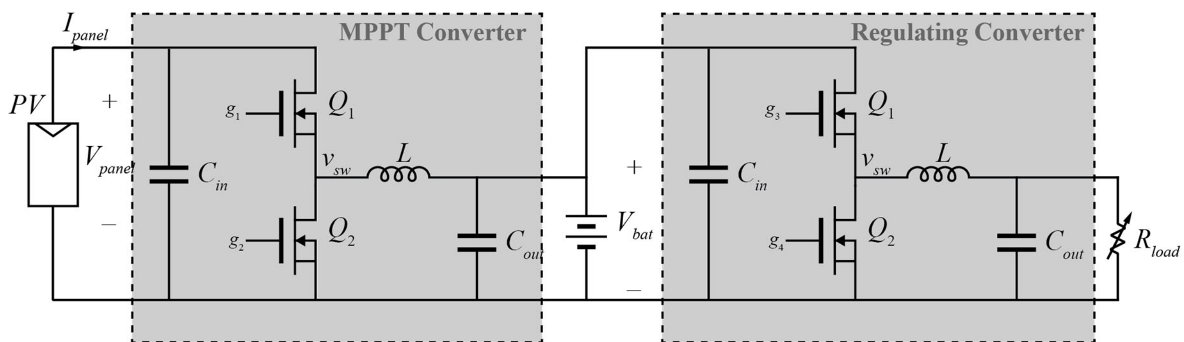

Fig. 1: Complete solar USB charger. System has one converter which is controlled to provide MPPT, and one converter to regulate a 5V output.

The first converter is controlled to track the panel's maximum power point, while the second converter is controlled to regulate a fixed, 5V output. In this experiment, we will develop and experimentally measure the control-to-output transfer function of the second converter, for use in developing a closed-loop control implementation.

We will use the same GaN-based synchronous buck converter power stage from Experiment 2. However, for this experiment we will not need to use the PV panel. Instead, the converter input is an 8V source, emulating the battery, and a 5Ω load at the output.

II. Procedure

In this experiment, we will measure the control-to-output transfer function

$$G_{vd}(s) = \frac{\hat{v}(s)}{\hat{d}(s)}$$

Once known, this transfer function can be used to design a compensator for stable, well-behaved closed-loop regulation as discussed in class. We will measure this transfer function by injecting a sinusoidal perturbation into the duty cycle and measuring the resulting perturbation on the output voltage.

a. Analytical Modeling

Before beginning the experiment, develop an analytical, small-signal, averaged and linearized model of the buck converter used in Experiment 2. Solve for your prediction for the control-to-output transfer function $G_{vd}(s)$

As a reminder, the components used in the converter are given in Table I.

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

b. Experimental measurement

The test setup for measuring $G_{vd}(s)$ is shown in Fig. 2. It consists of the following external connections:

- A power supply connected at V_g provides the 8V input voltage. This supply should be current-limited to 1A
- A separate supply connected to V_{cc} provides the control power. This supply should provide less than 100mA of current
- An electronic load, set to emulate a 5Ω resistance, is connected at the output.
- A function generator is used to set the duty cycle by providing V_{mod} to the pulse width modulator.

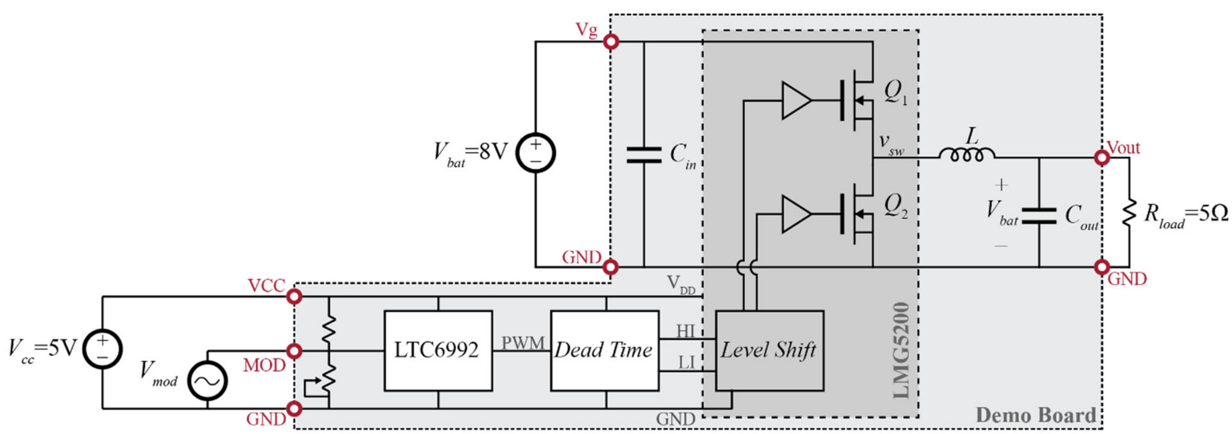

Fig. 2: Experimental testing setup for transfer function characterization

The LTC6992 pulse-width modulator's duty cycle is controlled by the voltage at V_{mod} according to the plot of Fig. 3 (V_{set} = 1V).

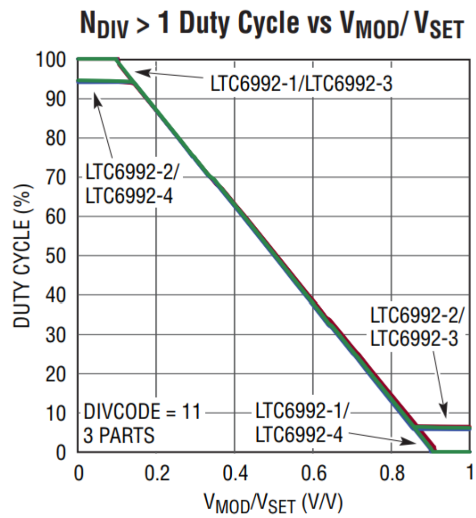

Fig. 3: Relationship between V_{mod} and duty cycle for the PWM used on the test board.

Note that the relationship between V_{mod} and D is inverting (i.e. greater V_{mod} means lower duty cycle).

We will be measuring the transfer function around a steady-state operating point with 8V input, 5V output, and 5Ω load. Around this operating point, we will perturb the duty cycle slightly, and measure the resulting perturbation in the output voltage in order to determine the magnitude and phase of the gain from $d(t)$ to $v(t)$. We will do this for one frequency at a time by using the function generator to set

$$V_{mod}(t) = V_{MOD} + A_{mod}\cdot\sin(\omega_x t) \tag{1}$$

Where V_{MOD} is the DC offset of the function generator, and $A_{mod}\cdot\sin(\omega_x t)$ is the AC perturbation with amplitude A_{mod} and frequency ω_x.

Applying this modulation voltage will cause the duty cycle to vary according to

$$d(t) = D + A_{mod}/V_M\cdot\sin(\omega_x t) \tag{2}$$

where D is the steady-state (DC) duty cycle and $A_{mod}/V_M\cdot\sin(\omega_x t)$ is the AC perturbation to the duty cycle. The frequency is the same as that of the modulation voltage and the amplitude of this perturbation is A_{mod}/V_M, where V_M is the carrier amplitude, $V_M = \partial v_{mod}(t)/\partial d(t)$, which can be read off of Fig. 3.

as a result of this duty cycle variation, the output voltage will be

$$v(t) = V + A_{mod}/V_M\cdot\|G_{vd}(j\omega_x)\|\cdot\sin(\omega_x t + \angle G_{vd}(j\omega_x)) \tag{3}$$

where V is the steady state value (5V) and $A_{mod}/V_M\cdot\|G_{vd}(j\omega_x)\|\cdot\sin(\omega_x t + \angle G_{vd}(j\omega_x))$ is the AC perturbation on the output voltage resulting from the duty cycle perturbation.

By measuring both $V_{mod}(t)$ and $v(t)$, using (1) and (3), we can solve for the magnitude $\|G_{vd}(j\omega_x)\|$ and phase $\angle G_{vd}(j\omega_x)$ of the control-to-output transfer function as some frequency ω_x. By doing this at multiple frequencies ω_x spanning the range from DC to $f_s/10$, we can fully characterize $G_{vd}(s)$.

The specific procedure to do this is as follows

- Connect one scope probe to the back of the function generator on the "Source 1" BNC connector. Using the "source" button on the front of the oscilloscope, turn on Source 1, and set it to output a sinusoidal wave. Start with a frequency of 100 Hz and an amplitude of 50mV. The offset should be the value that will give the correct duty cycle so that the converter will output 5V from an 8V input, in accordance with Fig. 3.

- Move the wiper of the (slider) potentiometer to the middle of the track. This potentiometer was previously used to set the duty cycle in experiment 2; we set it to the middle position so that it will not short out the function generator.
- Once the signal generator has been configured, connect the probe from the signal generator to V_{mod}. See Fig. 4 for the location of V_{mod} on the test board. Using a second probe, measure V_{mod} on Channel 1 on the front of the oscilloscope.

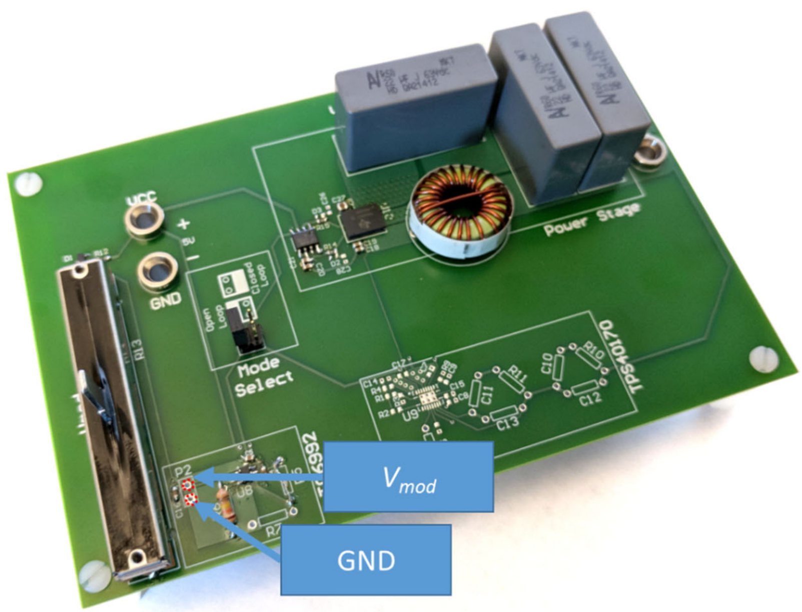

Fig. 4: Demo board used in Experiment 2, with the location of V_{mod} shown.

- Connect 5V to the VCC banana jacks on the board to power the PWM.
- Connect the electronic load to the output and set it to 5Ω resistance. Connect an additional probe on Channel 2 of the oscilloscope to measure the output voltage.
- Turn on the supply that will be used for the input voltage. Prior to connecting it, set the current limit to 1A and the voltage to the minimum. Connect it to the board, and slowly bring the voltage up from its minimum to 8V.
- Examine the output voltage. If it is not 5V, adjust the offset of the function generator (which sets the DC duty cycle) to correct it.
- Set the coupling of both Channel 1 and Channel 2 to AC. This will eliminate the DC offset and let you examine the AC perturbations with higher resolution.
- Set Channel 2 (the measured output voltage) to inverting. This will cancel out the inverting nature of the PWM chip (otherwise your measurements will be off by 180°).
- Save a screen capture from the oscilloscope of the two waveforms at this operating point (you only need to save a screen capture once, for the first operating point).

- Using the cursors and/or measurement functions of the scope, measure the amplitude of the sinusoid on the output voltage, the amplitude of the sinusoid on V_{mod}, and the time difference between the maximum values of both (A_{out}, A_{mod}, and t_φ, respectively, in Fig. 5). Record these values, as well as the frequency of the perturbation that you set in the function generator.

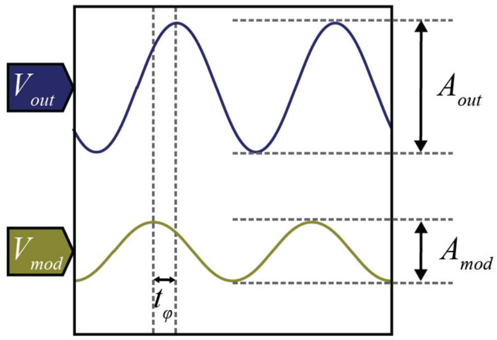

Fig. 5: Example scope waveforms with two probes measuring V_{out} and V_{mod}, with amplitudes and time differences shown.

- In the scope's function generator, increase the frequency of the perturbation, while keeping the amplitude at 50mV. Repeat the measurements for enough different frequencies to fully characterize the transfer function. You will need to select what frequencies to measure, but in general, you will want more points in the vicinity of poles/zeroes, and can use relatively fewer points in frequency ranges far from poles or zeroes. In any event, you should not go to frequencies higher than $f_s/10$.

c. Data Conversion and Plotting

Based on equations (1), (2), and (3), manipulate your measurements to solve for $||G_{vd}(j\omega_x)||$ for each of the frequencies $f_x=2\pi\omega_x$ that you measured. The phase, in degrees is

$$\angle G_{vd} = -t_\varphi f_x \cdot 360° \quad (3)$$

Based on your N different frequency measurements, you should have arrays of measured data of length N for the frequency, magnitude, and phase. Enter these into the provided MATLAB script, along with your model of the buck converter control-to-output transfer function. The script should plot the analytical and measured results on the same bode plot. Comment on any discrepancy