Experiment #4

Converter Small-Signal AC Transfer Functions

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The objectives of this experiment are:

- To experimentally measure the control-to-output transfer function $G_{vd}(s)$ of your converter prototype
- To model and simulate this transfer function
- To damp the internal resonance of the SEPIC

1. Measurement of $G_{vd}(s)$

Figure 1 illustrates measurement of the control-to-output transfer function $G_{vd}(s)$ of your SEPIC.

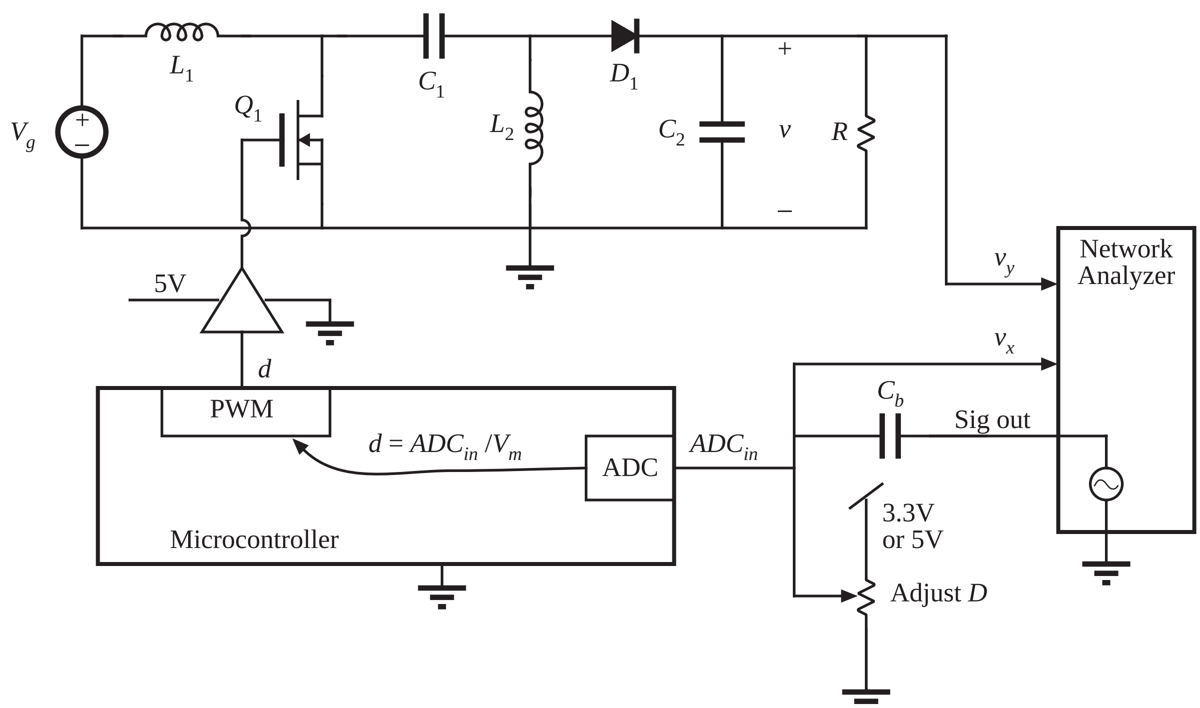

Figure 1 Measuring G_{vd} of the SEPIC.

You will use the Network Analyzer function of the Analog Discovery 2 device to measure the small-signal ac transfer function of your converter. A detailed guide to the network analyzer function of the AD2 is linked to the course site. The course site also includes a video lecture on measurement of small-signal ac transfer functions.

For this experiment, you will use the microcontroller as a pulse-width modulator, producing an output PWM signal whose duty cycle d is proportional to an input signal ADC_{in} applied to an analog-to-digital converter input pin. The course site includes a zip file containing a Code Composer project that can both read the ADC and output a duty cycle. You should edit this code such that the output duty cycle is proportional to the instantaneous ADC input voltage, leading to an effective PWM gain of $d/ADC_{in} = 1/V_m$. In the circuit of Fig. 1, the analog voltage ADC_{in} consists of a dc component set by a potentiometer, plus an ac component generated by the network analyzer. The dc component is intended to set the quiescent duty cycle and the quiescent operating point of the SEPIC. The ac component is intended to create a small-signal ac variation of the duty cycle.

Connect the potentiometer to the ADC input pin as illustrated in Fig. 1. Observe the PWM output signal using the AD2 operating in oscilloscope mode. Verify that you are able to adjust the potentiometer to vary the PWM duty cycle. Adjust the quiescent duty cycle to the correct value for your SEPIC with $V_g = 17$V, $V = 12.5$V, and load resistance of 30Ω. Use your multimeters to record V_g and V.

Connect the AD2 network analyzer signals and the potentiometer and blocking capacitor C_b as shown in Fig. 1. Operate your SEPIC with a dc power supply input of 17 V and a load resistor of 30Ω. With your ADC/PWM code running, measure the transfer function using the AD2 network analyzer. It is necessary to set up this measurement as follows:

- The ac component of the signal at ADC_{in} should have amplitude much less than the dc component set by the potentiometer. This ensures that the small-signal assumption is satisfied.
- The ac component of the signal at ADC_{in} should have amplitude large enough that the signals v_x and v_y are above their respective noise levels, and hence the measured transfer function data is not overly noisy.
- The frequency response measurements should be limited to frequencies less than half of the converter switching frequency. At frequencies approaching and above this limit, sampling of the PWM and ADC significantly affect the transfer function.

Record the measured magnitude and phase transfer function, and include in your report. Note that this measurement is $G_{vd}(s)/V_m$.

2. Simulation of $G_{vd}(s)$

The course site includes a lecture on use of LTspice to simulate the ac transfer functions of switching converters using averaged switch models such as CCM-DCM1. Use LTspice with CCM-DCM1 to simulate the small-signal control-to-output transfer function of your SEPIC at the quiescent operating point of part 1 above. Plot both magnitude and phase, over the frequency range you measured in part 1.

3. Damping the Internal Resonance

The course site includes a lecture on modeling the SEPIC small signal $G_{vd}(s)$ transfer function, and damping its internal resonance. The lecture employs Middlebrook's extra element theorem to show that the SEPIC $G_{vd}(s)$ transfer function can be expressed as that of an effective buck-boost converter (having quadratic poles and a RHP zero), multiplied by a correction factor that can have resonant poles and zeroes arising from the internal capacitor C_1 and the inductors $(L_1 + L_2)$.

Evaluate the effective buck-boost model to find its predicted $G_{vd}(s)$ for your SEPIC, and compare with your measured data. Do these agree? How do they deviate, if at all?

Evaluate the internal resonance frequency

$$f_{int} = \frac{1}{2\pi\sqrt{C_1(L_1 + L_2)}} \tag{1}$$

Does your measured G_{vd} exhibit deviations from the effective buck-boost transfer function in the vicinity of the frequency f_{int}? Depending on your element values and your converter losses, it is possible that the internal resonance of your original converter power stage will be damped to the point that it is not visible. But most likely your $G_{vd}(s)$ will be significantly impacted by this resonance.

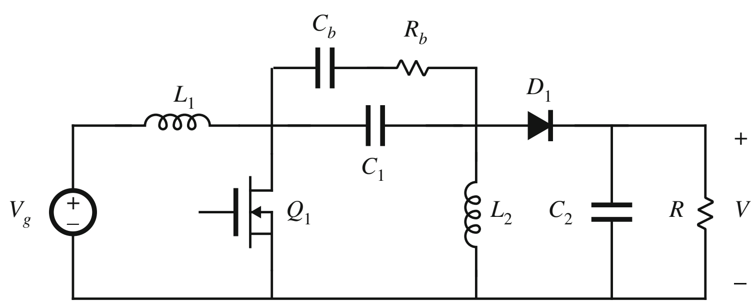

Figure 2 Addition of R_b–C_b network to damp the internal resonance of the SEPIC.

Use semilog axes to plot the impedances

$$Z_L = (sL_1 + sL_2) \tag{2}$$

and

$$Z_{C1} = \frac{1}{sC_1} \tag{3}$$

Add damping network

$$Z_b = R_b + \frac{1}{sC_b} \tag{4}$$

as illustrated in Fig. 2 and the video: select R_b so that the intersection of the impedance Z_L with the damped impedance

$$Z = Z_{C1} || Z_b \tag{5}$$

occurs where Z is dominated by R_b. It will be necessary to choose the blocking capacitor C_b to be two or more times larger than C_1.

Add this damped impedance Z to your LTspice model of part 2, and repeat the simulation of $G_{vd}(s)$. You may want to further adjust your choice of R_b and C_b so that the result is well damped and exhibits only small deviations from the effective buck boost transfer function.

Implement this damping network in your experimental SEPIC. Repeat the measurement of the experimental $G_{vd}(s)/V_m$ to verify that the internal resonance is sufficiently damped.

Grading Rubric

1. Measurement of original $G_{vd}(s)$

(30 points total)

- Report multimeter readings of quiescent values of V_g and V. Values should be within ±1V of the required values. (3 points)
- Measured Bode plot of magnitude and phase of G_{vd}/V_m. Some moderate noise in the plots is allowable, but the underlying magnitude and phase data should be discernable and should appear to represent a valid transfer function. (24 points)
- What is the numerical value of the PWM/ADC gain $1/V_m$? This is the gain from a perturbation in the ADC input voltage to the resulting perturbation in the PWM output duty cycle. It can vary depending on the selected switching frequency and on any scale factors employed in the interrupt service routine. The calculation of this gain should be documented briefly. (3 points)

2. Simulation of $G_{vd}(s)$

(30 points total)

Document your LTspice simulation of your SEPIC. Include your LTspice schematic or netlist (10 points). Include your output Bode plots of the magnitude (7 points) and phase (7 points) of $G_{vd}(s)$. Briefly discuss any deviations between your simulation and your measurement of part 1 (6 points).

3. Damping the internal resonance

(40 points total)

- Evaluate the $G_{vd}(s)$ transfer function of the effective buck-boost converter model, described in the accompanying lecture. Give numerical values for the salient features (poles, zeroes, dc gain). Compare with your measurements of part 1: how do those measurements deviate from the predictions of the effective buck-boost model? (5 points)
- Evaluate the internal resonance frequency, Eq. (1). Discuss whether you observe evidence of this resonance in your experimental measurements of part 1, or in your simulation of part 2. (5 points)

- Plot the magnitudes of the impedances Z_L and Z (Eqs. (2) and (5)) for your final design, and report your element values. (10 points)
- Document your LTspice simulation of your damped SEPIC of part 3. Include your LTspice schematic or netlist. Include your output Bode plots of the magnitude and phase of $G_{vd}(s)$. (10 points)
- Give your measured Bode plot of the damped $G_{vd}(s)$ magnitude and phase for your experimental SEPIC with damping network. Is the internal resonance sufficiently damped? (10 points)