Experiment #5

Closed-Loop Voltage Regulator

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The objectives of this experiment are:

- To design and implement a feedback that regulates the output voltage of your converter
- To verify your loop gain and phase margin
- For those earning graduate credit (ECEN 5517): to implement digital control
- To measure outtput voltage regulation for variations in the load current and input voltage

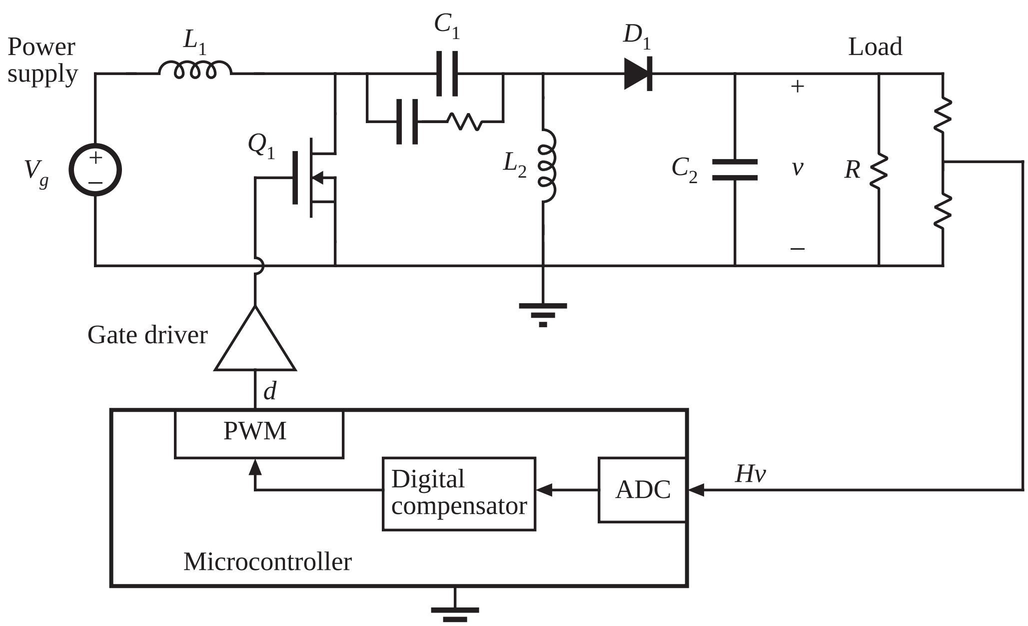

Figure 1 Closed-loop SEPIC system with digital control.

In this experiment, you will design, build, test, and demonstrate a closed-loop control system that regulates the output voltage of your SEPIC dc-dc converter. Figure 1 is a high-level depiction of a possible realization; you will design additional analog circuitry and/or digital algorithms as described below.

You should design your feedback system to work well at the following operating point and conditions:

- Input voltage V_g: dc power supply, providing 17 V
- Output V: 12.5 V across a 30Ω load resistor
- Phase margin $\varphi_m \geq 52°$

Design the best feedback loop you can. It will be necessary that your closed-loop system operates at other quiescent points, according to the range of input voltages and powers that your PV panel can provide, but for this experiment you should at least design for the operating point described above.

For students earning ECEN 5517 credit, your feedback loop must include the following:

- Crossover frequency $f_c \geq 1$ kHz
- Compensator implementation: digital controller

For students earning ECEN 4517 credit: you may employ either an analog or a digital controller. There is no requirement regarding crossover frequency, but again, design the best compensator that you reasonably can.

1. Compensator and Analog Circuitry Design

The object of this part is to build a feedback loop that regulates the output voltage $v(t)$ of your dc-dc SEPIC. You should design and construct analog circuitry that senses the dc output voltage $v(t)$, divides this voltage to a lower magnitude appropriate for connection to the ADC input, and possibly includes circuitry for interfacing to the ADC terminal. If you are implementing an analog error amplifier and compensator, then you will need to design that circuitry also. If you are implementing a digital controller, then you should design your digital compensator instead. In either event, your compensator transfer function should be based on your measured $G_{vd}(s)$ from Experiment 4, and on the predicted transfer functions of the remaining elements in your feedback loop. You may choose to change the converter element values and the resulting $G_{vd}(s)$, if you wish.

For your report, document the theoretical transfer function of each block in your loop, and the loop gain magnitude and phase. Also report the predicted phase margin and crossover frequency at the nominal operating point defined above. Document the complete schematic of your closed-loop circuit and the part of your microcontroller code that is relevant to your feedback controller.

2. Startup and Large Signal Stability

When losses are included, the familiar dc output voltage curve V/V_g vs. D reaches a maximum value at some large value of D, and goes to zero at $D = 1$. This can cause the control system to hang up at large duty cycle, especially during the start up transient. For this reason, it is necessary to limit the maximum duty cycle to a value that is greater than the expected quiescent duty cycle, but low enough that the feedback loop converges to the desired operating point.

Similarly, current limiting of the input power supply can cause the closed-loop system to hang up at low input voltage: with low output voltage, the feedback loop may increase the duty cycle such that the input current is increased to the power supply current limit. The power supply then operates in current limit mode with low input voltage, and the closed-loop system does not reach the desired output voltage. Traditionally, this problem is mitigated using current limiting or a soft start circuit.

Implement limiting of the maximum duty cycle ($d \leq D_{max}$). If necessary, also implement soft start or current limiting, so that your closed-loop regulator will reliably start up when the power supply is switched on, and hence the closed-loop output voltage reaches the desired quiescent value.

In your report, document what circuitry and/or code you added to implement the above functionality such that the closed-loop regulator starts reliably.

3. Loop Gain Measurement

With your closed-loop system regulating at the nominal operating point defined above, measure the small-signal loop gain using a network analyzer. Evaluate the crossover frequency and phase margin.

In your report, document the measured loop gain magnitude and phase. Fit asymptotes to the magnitude and phase data, that follows all of the usual asymptote rules such as magnitude slopes that are multiples of 20 dB/decade, etc. Hence deduce the loop gain transfer function including its poles, zeroes, and gain. Compare your measured loop gain, crossover frequency, and phase margin with the theoretical loop gain from Part 1. Does your phase margin meet the requirements?

4. Regulation

Steady-steady closed-loop regulation of the output voltage is defined as

$$\frac{\Delta V}{V} = \frac{V_{max} - V_{min}}{V_{nominal}} \times 100\%$$

The voltage is evaluated when the feedback loop operates in equilibrium, and one parameter such as load current or input voltage varies over a specified range. At each data point, measure the steady-state duty cycle D, dc input voltage V_g, and dc output voltage V. The nominal output voltage should be taken to be $V_{nominal} = 12.5$ V.

Voltage regulation with load current variation

With the input voltage set to $V_g = 17$ V, measure the closed-loop equilibrium output voltage V with load resistances of 15Ω, 30Ω, 60Ω, and open-circuit. Compute the voltage regulation for this range of load resistances.

Voltage regulation with input voltage variation

With the load resistor set to a constant value of 30Ω, measure the closed-loop equilibrium output voltage V with input voltages of 14 V to 21 V in steps of no more than 1 V. Compute the output voltage regulation for this range of input voltages.

In your report, list the data taken in your load current and input voltage tests. Report the voltage regulation for both tests.

Grading Rubric

1. Documentation of system design

(40 points total)

- Give a block diagram of your feedback system, and document the transfer function of each block in your loop.
- Construct the magnitude and phase asymptotes of the loop gain of your system, and report the theoretical crossover frequency and phase margin.
- Document the complete schematic of your final closed-loop circuit for Exp. 5.
- Document the part of the microcontroller code that is relevant to your feedback controller (i.e., the interrupt service routine).

2. Startup and large-signal stability

(15 points total)

Describe what you did to make your closed-loop system start up. Document how you limited the maximum duty cycle, and the value of D_{max} that you used. If you implemented soft start or current limiting, document what you did and the associated circuitry or code.

3. Loop gain measurement

(35 points total)

Report your measured loop gain magnitude and phase. Construct magnitude and phase asymptotes of your loop gain, that follow all of the standard rules for asymptote slopes and break frequency. Report the loop gain transfer function for your measurement, and give numerical values for the salient features (i.e., the corner and break frequencies, gains, Q, etc. as appropriate). Report the measured crossover frequency and phase margin. Compare your results with your theoretical predictions of part 1.

4. Regulation

(10 points total)

For your voltage regulation with load current variation test, report the measured duty cycle, dc input voltage, dc output voltage, and load resistance for each step. Calculate the voltage regulation based on this data.

For your voltage regulation with input voltage variation test, report the measured duty cycle, dc input voltage, and dc output voltage for each step. Calculate the voltage regulation based on this data.