Overview

In this lab, you will add feedback to your buck/boost converter. The controller will hold the output voltage at a set point by automatically adjusting the duty cycle control signal to the MOSFET firing circuit.

Introduction

A proportional-integral controller (i.e., PI) with feedback can take the place of manual adjustment of the switching duty cycle to a DC-DC converter and act much more quickly than is possible "by hand." Consider the Transformer, DBR, MOSFET Firing Circuit, DC-DC Converter, and Load as "a process" shown below. In the open loop mode that you used last time, you manually adjusted duty cycle voltage Dcont.

$$\begin{array}{c} \text{Dcont} \\ (0-3.5\text{V}) \longrightarrow \end{array} \begin{array}{c} \text{Transformer, DBR, MOSFET} \\ \text{Firing Circuit, DC-DC} \\ \text{Converter, and Load} \end{array} \begin{array}{c} \text{V}_{\text{out}} \\ (0-120\text{V}) \end{array}$$

Figure 1. Open Loop Process

To automate the process, the "feedback loop" is closed and an error signal (+ or -) is obtained. The PI controller acts upon the error with parallel proportional and integral responses in an attempt to drive the error to zero.

Let αV_{out} be a scaled down replica of V_{out} . When αV_{out} equals V_{set} , then the error is zero. A resistor divider attached to V_{out} produces αV_{out} , which is suitably low for op-amps voltage levels.



Figure 2. Closed Loop Process with PI Controller

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The Circuit

A detailed circuit layout of the PI controller is given in Figure 3. A total of six op-amps are used – two as buffer amplifiers, one for error, one for proportional gain, one as an integrator, and one as a summer. Since the op-amp chips are duals, three op-amp chips are required to implement the PI controller. We use four to de-clutter the circuit. Left to right, op amps #1 and #2 are in one chip, op amps #3 and #4 (not used) are in one chip, op amps #5 and #6 are in one chip, and op amps #7 and #8 (not used) are in one chip. Inputs to unused op amps are grounded. Boxes link this figure to measurement locations in Figure 4.



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board.



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The Experiment

In this experiment, you will power a buck/boost converter with a DBR, and use the controller to hold regulated **80V to a 150W incandescent light bulb**. Operate your buck/boost converter at about **100kHz**.

Step 1. Getting Started

- All chips (DIP and SIP) are socketed. Keeping chips in a socket helps preserve their pins for future use.
- Use nylon hardware to physically connect a MOSFET firing circuit to your PI controller, overlapping as shown in Figure 4.
- Solder wires through the overlapping +12V- holes and the –Dcont+ holes so that the boards share wall wart power and that Dcont from the controller feeds to the firing circuit.
- Set the SPDT switch of the MOSFET firing circuit to the left position for "External Duty Input."

Step 2. The Set Point

- DO NOT power up the DBR in this step.
- Set Proportional potentiometer fully counterclockwise (minimum Kp).
- Set Integrator potentiometer fully counterclockwise (minimum K_j).
- SWITCH OFF the Feedback and Integrator SPDT switches.
- Power up the combined MOSFET Firing Circuit and PI Controller.
- Check the isolated +12V and -12V outputs on the PI controller to make sure they are OK. Voltages below 11V indicate a short circuit in your wiring, which will burn out the DC-DC chip in a few minutes.

- View V_{GS} on an oscilloscope and confirm that the waveform is clean and has a switching of about 100kHz.
- Adjust Set Point Potentiometer so that $V_{set} \approx 1.41V$. V_{set} is the "target voltage" of the controller, which roughly corresponds to $V_{out} = 80V$. It can be fine-tuned later.

Step 3. The D Limiter

- DO NOT power up the DBR in this step.
- View V_{GS} on an oscilloscope.
- **SWITCH ON the Integrator SPDT switch** to drive the integrator's output to its rail (10+ volts).
- Adjust the D Limiter so that the duty cycle of V_{GS} is approximately 0.85. The objective is to prevent the PI controller from rising to the D = 1 condition which would short circuit the MOSFET.
- SWITCH OFF the Integrator SPDT switch, and make sure the Integrator potentiometer is fully counterclockwise.

Step 4. Set the Open Loop Gain to Unity

- Make sure the Integrator SPDT switch is off.
- Connect a 150W incandescent light bulb to the output of the buck/boost converter.
- With a variac, 120/25V transformer, and DBR toggle switch on, slowly raise the variac until the DBR output voltage is the usual 35-40V.
- While viewing V_{GS} , **slowly raise** the Proportional K_p Potentiometer until the converter output voltage is $80V \pm 2V$. D may be jumpy and unstable, and there may be noticeable oscillation on V_{GS} . Small actions such as touching the MOSFET heat sink or measuring a voltage on the PI controller board may change the V_{GS} waveform and light bulb brightness, or cause light bulb flicker. These are all signs of instability. At 80V, the K_p potentiometer should be slightly past mid-range.
- Re-check your DBR voltage to make sure it did not drop more than 2-3 volts. If it did, re-adjust the variac and K_p to achieve 80V output.
- **SWITCH OFF the DBR toggle switch.** The clean duty cycle measurement on the scope should be about 0.7.
- Unplug the wall wart. Measure R_{p1} between the middle and right-hand prongs. My value was $67k\Omega$. The ratio R_{p1} / R_{p2} is the proportional gain needed to yield unit process gain. My gain value for unity was thus 67 / 10 = 6.7. Process K_p will be normalized to this $67k\Omega$ setting.

Step 5. Perform the Open Loop Bump Test to Observe the Process Time Constant T

- Make sure the Integrator SPDT switch is off.
- Connect channel 1 probe to V_{out}.
- Plug in the wall wart, and SWITCH ON the DBR toggle switch.
- Set time scale to 20msec/division, and voltage scale to 20V/division.
- Select averaging, with 1 cycle.

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- Set trigger mode to normal, and adjust the trigger voltage to about 10V.
- Set trigger so that triggering occurs on positive-going change.
- Press "single" to freeze the screen on the next trigger.
- SWITCH OFF AND BACK ON the DBR toggle switch and capture the open loop response of the process and freeze it. Save a screen snapshot for your report. Upon careful examination of the saved screen snapshot, using both 20 and 5 msec/division scales on the scope, two time constants can be observed in the response. The slow one, in Figure 5, is due to the dynamics of the transformer and DBR. The fast one, in Figure 6, is due to the dynamics of the converter itself. Two time constants are often observed when switching large capacitors in power systems and is explained by the concept of "voltage equalization" as follows: for the first few msec, the DBR capacitor and equivalent converter resistance, form a series circuit. The DBR capacitor voltage falls slightly, and the converter capacitor voltage rises significantly. Charge is conserved. The two capacitors then act in parallel with a common voltage. The dynamics of the transformer plus DBR take effect, replenishing the DBR and converter capacitors gradually.



• For our purposes, the DBR cap is essentially fully charged when Vout is being controlled. Thus, it is appropriate for us to use the fast time constant as our process time constant T. Estimate T from Figure 6 as the time required to rise to $(1 - e^{-1}) = 0.63$ of the asymptote. Expect T to be about 2 msec. This corresponds to the RC product of converter output capacitance (1500 to 1800 µF) and converter resistance $R = -\frac{\partial V}{\partial I}$ (i.e., about one ohm of Thevenin equivalent resistance).

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Figure 5. The Slow Time Constant of V_{out} during the Open Loop Bump Test



Figure 6. The Fast Time Constant of V_{out} during the Open Loop Bump Test (this is a 5 msec/div scale zoom-in of Figure 5)

Step 6. Close the Feedback Loop, Check for Oscillation due to Kp

- With the lightbulb on, **SWITCH ON the Feedback SPDT Switch**. The light bulb will dim because the feedback voltage reduces the error signal.
- Observe and take note of the knob position of K_p. Then, sweep K_p through its range, starting from full counter-clockwise to full clockwise. If an oscillation develops, such as light bulb flicker or flicker in V_{GS}, back up on K_p until the oscillation subsides and then a bit farther.

Step 7. Set Kp

- SWITCH OFF the DBR, and unplug the wall wart
- Tuning recommendations are for process $K_p = 0.45$, normalized to our unity process gain. This means you should adjust your R_{p1} so it is 0.45 times its present value. For me, the new setting for R_{p1} was $67k\Omega \bullet 0.45 = 30k\Omega$.

Step 8. Turn on the Integrator and Carefully Sweep Integrator Time Constant T_i to Find the Boundary of Instability

- Feedback SPDT Switch should be ON.
- Plug in the wall wart, and SWITCH ON the DBR
- Make sure the Integrator potentiometer is fully counterclockwise.
- SWITCH ON the Integrator SPDT. The light bulb will immediately brighten because the controller quickly raises V_{out} to the 80V target value.
- If needed, raise the variac so that the DBR output voltage is 40V.
- If your output voltage is outside $80V \pm 2V$, tweak the V_{set} potentiometer.
- While watching V_{GS} on the scope, carefully lower T_i by slowly rotating the Integrator Potentiometer clockwise until signs of oscillation occur in V_{GS} and/or you detect audible buzzing. Buzzing may not be noticeable in these improved PC circuit boards. However, if you hear buzzing, SWITCH OFF the DBR toggle switch. Buzzing is bad news in any power electronic circuit and usually means that circuit failure is imminent.
- Unplug the wall wart.
- Measure the net R_i at the onset of instability as follows: Measure the Integrator potentiometer resistance by connecting an ohmmeter between the left-hand and middle prongs. Mine was 5.2k Ω . Then add the series $3.3k\Omega$ resistor to your reading. The sum is net R_i . My net R_i at the point of instability was then $5.2k\Omega + 3.3k\Omega = 8.5k\Omega$. Thus, with two parallel 0.01μ F caps, so $C_i = 0.02\mu$ F, my computed controller stability boundary for $T_i = R_iC_i$ is about 0.2 msec. We want to keep T_i above this value. The purpose of the $3.3k\Omega$ resistor is to prevent infinite integrator gain and serious burnout oscillations.

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Step 9. Set the Integrator Time Constant T_i

- The integrator should be faster than the process, but not so fast to create instability (such as buzzing). PI tuning rules recommend that integrator time constant T_i = R_iC_i be approximately 0.8 times T of the process. For our case, T ≈ 2 msec from Step 5, so using the suggested 0.8 2 msec yields T_i = 1.6 msec. With C_i = 0.02µF, then the optimum value for R_i should be around 80kΩ.
- Use an ohmmeter to adjust your $R_{i1} = 77k\Omega$ to achieve $R_i = R_{i1} + R_{i2} = 80k\Omega$.

Step 10. Perform the Variac Test

- Plug in the wall wart, and SWITCH ON the DBR toggle switch
- While observing V_{GS} , quickly raise and lower the variac voltage. The controller should hold the light bulb brightness constant to the eye, except when the variac voltage is so low that the duty cycle limit is reached. Watch how V_{GS} changes as you turn the variac knob, and how D hits the upper limit.
- All signs of instability should have disappeared, such as when you touch the heat sink, etc. However, touching any op amp terminal with a multimeter lead usually creates noticeable lightbulb change and buzzing.

Step 10. Perform the Closed Loop Bump Test for the Complete PI Controller, and Vary the Parameters





Step 11. Test your PI controller by providing 13.2V to two 5Ω resistor in parallel. Do not accidently apply 80V to the resistors! The integrator time constant will not change, but you will need to make the circuit changes on Page 4, and reset your Kp for 13.2V. The set point should still be about 1V. Take snapshots as before.



Step 12 (Optional), Solar application for providing 13.2V. With good sun, repeat Step 11 using a solar panel pair. To steady the panel current, put a DBR between the panel pair and your converter. That will place the DBR's output cap across the panel. Use a 5Ω resistor as your converter load, which will draw about 1A from the panels. Observe V_{GS}.

You will find it necessary to turn off the integrator switch **before** you energize the circuit with solar panels. Once energized, then turn on the integrator switch. Reason? If the integrator is on before the panels are switched on, the integrator has already driven D to the limit, and the controller responds to low Vout by trying to raise D. But D is already at the upper limit, and the panels are in the short circuit condition.

What is actually needed in that situation is to lower D. But that is opposite the conventional PI logic. Thus, the concept of raising D to raise Vout fails once the panel voltage is below the peak power point. By starting with low D, the PI controller is able to raise Vout.

So, what do you think happens if a cloud shadow comes over and the panels cannot provide the 13.2V to the load? Will the PI controller recover once the sun returns?

Appendix. Analysis of the Transfer Function

The circuit in Figure 2 represents the standard negative feedback block diagram with transfer function

$$\frac{V_{out}(s)}{V_{set}(s)} = \frac{G(s)}{1 + G(s)H(s)}, \text{ with } H(s) = 1.$$

Thus, we have

$$\frac{V_{out}(s)}{V_{set}(s)} = \frac{G(s)}{1+G(s)} , \qquad (A1)$$

where G(s) is the open loop transfer function. In our case, G(s) is the product of the two transfer functions

$$G(s) = G_{PI}(s) \bullet G_{TRANS+DBR+MOSFETFIRINGCIRCUIT+DCDCCONVERTER+LOAD}(s).$$
(A2)

The second term is the process transfer function $G_{process}(s)$. For the PI controller, the parallel proportional and integral components yield

$$G_{PI}(s) = K_P + \frac{1}{sT_i},\tag{A3}$$

where

$$T_i = R_i C_i.$$

For the process, 1.5V input yields V_{out} (scaled) = 1.5V in steady-state, so the gain of the process here is 1.0. The converter exhibits the classic exponential rise time (i.e., charging capacitor), where C is the DC-DC output capacitor, and R is the fast Thevenin equivalent $\left(-\frac{\partial V}{\partial I}\right)$ of the process. Thus, the process transfer function is approximated with

$$G_{process}(s) = \frac{1}{1+sT} \quad , \tag{A4}$$

where T = RC.

Substituting (A3) and (A4) into (A2) yields

$$G(s) = \left(K_P + \frac{1}{sT_i}\right) \bullet \frac{1}{1 + sT}$$
 (A5)

Substituting (A5) into (A1) yields

$$\frac{V_{out}(s)}{V_{set}(s)} = \frac{\left(K_P + \frac{1}{sT_i}\right) \bullet \frac{1}{1+sT}}{1 + \left(K_P + \frac{1}{sT_i}\right) \bullet \frac{1}{1+sT}} = \frac{\left(sT_iK_P + 1\right) \bullet \frac{1}{1+sT}}{sT_i + \left(sT_iK_P + 1\right) \bullet \frac{1}{1+sT}} = \frac{\left(sT_iK_P + 1\right)}{(1+sT)sT_i + \left(sT_iK_P + 1\right)},$$

$$\frac{V_{out}(s)}{V_{set}(s)} = \frac{T_iK_P\left(s + \frac{1}{T_iK_P}\right)}{s^2TT_i + sT_i\left(1+K_P\right) + 1} = \frac{\frac{K_P}{T}\left(s + \frac{1}{T_iK_P}\right)}{s^2 + s\left(\frac{1+K_P}{T}\right) + \frac{1}{TT_i}}.$$
(A6)

The denominator is the key to the response of the circuit when "bumped" by a unit step. The denominator has the standard form

$$s^2 + 2\zeta \omega_n s + \omega_n^2$$
.

In our case,

$$\omega_n^2 = \frac{1}{TT_i} , \qquad (A7)$$

$$1 + K_n$$

$$2\zeta\omega_n = \frac{p}{T}$$

Solving for K_p yields

$$K_{p} = 2\zeta \omega_{n} T - 1 = \frac{2\zeta T}{\sqrt{TT_{i}}} - 1 = 2\zeta \sqrt{\frac{T}{T_{i}}} - 1 .$$
(A8)

PI tuning procedures often call for T_i to be set to 0.8T, which means that $\zeta > 0.447$ for feasible K_p .

Settings of $T_i = 0.8T$, $\zeta = 0.65$, $K_p = 0.45$ appear to work well in this application when using a DBR. Note that the 120Hz ripple is eliminated. Some fine tuning of T_i and K_p will probably be necessary in your circuit.



- $V_{out} = K(V_+ V_-)$, K large (hundreds of thousands, or one million).
- $I_+ = I_- = 0.$
- Voltages are with respect to power supply ground.
- Output current is not limited.

Buffer Amplifier (converts high impedance signal to low impedance signal)



Inverting Amplifier (used for proportional control signal)



$$-V_{out}\left(\frac{1}{KR_{in}} + \frac{1}{KR_f} + \frac{1}{R_f}\right) = \frac{V_{in}}{R_{in}}.$$
 For large K, then $\frac{-V_{out}}{R_f} = \frac{V_{in}}{R_{in}}$, so $V_{out} = -V_{in}\frac{R_f}{R_{in}}$

Inverting Difference (used for error signal)



$$V_{out} = K\left(\frac{V_b}{2} - \frac{V_a + V_{out}}{2}\right), \text{ so } V_{out} + K\frac{V_{out}}{2} = K\left(\frac{V_b - V_a}{2}\right), \text{ or } V_{out}\left(1 + \frac{K}{2}\right) = K\left(\frac{V_b - V_a}{2}\right).$$

For large K, then $V_{out} = -(V_a - V_b)$.

Inverting Sum (used to sum proportional and integral control signals)



Substituting for V_{-} yields $3\left(\frac{-V_{out}}{K}\right) = V_a + V_b + V_{out}$, so $V_{out}\left(\frac{-3}{K} - 1\right) = V_a + V_b$. Thus, for large K, $V_{out} = -(V_a + V_b)$

Inverting Integrator (used for integral control signal)



Lower R_i or C to increase integrator response.

Inverting Differentiator



$$V_{out} = K(V_+ - V_-) = K(0 - V_-)$$
, so $V_- = -\frac{V_{out}}{K}$.

KCL at the – node is

$$\frac{V_- - V_{out}}{R_f} + C \frac{d}{dt} (V_- - V_{in}) = 0$$
. Eliminating V_-

yields

$$\frac{\frac{-V_{out}}{K} - V_{out}}{R_f} + C\frac{d}{dt}\left(\frac{-V_{out}}{K} - V_{in}\right) = 0.$$
 For large K, we have $\frac{-V_{out}}{R_f} + C\frac{d}{dt}\left(-V_{in}\right) = 0$, so

$$V_{out} = -R_f C \frac{dV_{in}}{dt}$$
. Raise R_f or C to increase differentiator response.

Butterworth Low-Pass Filter



Place the demonimator's breakpoint at ω_0 . Setting the two R's equal leads to

$$R = R_1 = R_2 = \frac{1}{\omega_o \sqrt{C_1 C_2}}$$
 and $\zeta = \sqrt{\frac{C_2}{C_1}}$.

It is clear from the ζ equation that underdamped response requires $C_2 < C_1$.

If we want $f_o = 100kHz$, then $\omega_o = 2\pi \cdot 100kHz$. Selecting C₁ = 1 nF and C₂ = 100 pF, then *R* should be approximately 5 k Ω (use 4.7 k Ω). The corresponding

$$\zeta = \sqrt{\frac{C_2}{C_1}} = 0.316.$$

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1. Example of PV Isolator Circuit. Overview

You will your PI controller with a buck converter to efficiently step down a solar panel pair voltage to a regulated 13.8V for safely powering automotive-type equipment. Because the MOSFET source terminal of a buck converter is not the same as the converter's reference, some form of isolation between the Vout of the converter and the PI controller feedback terminal is needed. This can be in the form of an isolated MOFET driver chip, or some other more general form of optical isolation. In this experiment you will use an International Rectifier Photovoltaic Isolator, PVI1050N. The PV chip has two halves, each with an internal LED light source and tiny solar cells whose short circuit current is proportional to the LED current. We series the input LEDs, and parallel the output cells.



2. Example Circuit

Figure 1. Example PV Isolator Circuit

The circuit needs two biasing resistors – one for input, and the other for output. Extra slots are provided in case you use parallel combinations.

3. Select the Resistor Values

Select the input resistor so that max buck/boost converter output voltage produces rated PV chip current (20mA). 120V rated will provide plenty of headroom to see overshoots on the normal 80V output of the converter. Example: $120V / 20mA = 6k\Omega$. Use a $10k\Omega$ resistor, 5W resistor. Resistor power check, $120^2/10000 = 1.4$ W. Note – double the power rating to prevent hot resistors.

20mA PV chip input current produces 40μ A PV chip output short circuit current. In this case, "short circuit" means that the output voltage is less than PV chip rated 4V output. 40μ A through a $100k\Omega$ resistor yields 4V. Power check = tiny. Thus, use $100k\Omega$.

4. Apply 13.8Vdc to the PV Isolator Circuit and Measure αVout (which will be your PI Set Point Voltage)





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