Williams

Power Electronics, PI Controller for DC-DC Boost Converter
Version April 05, 2018

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.

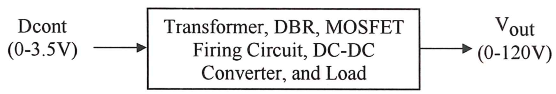


Figure 1. Open Loop Process

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.

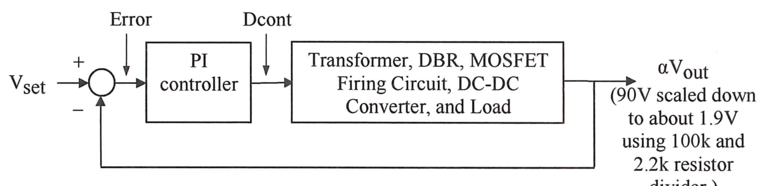
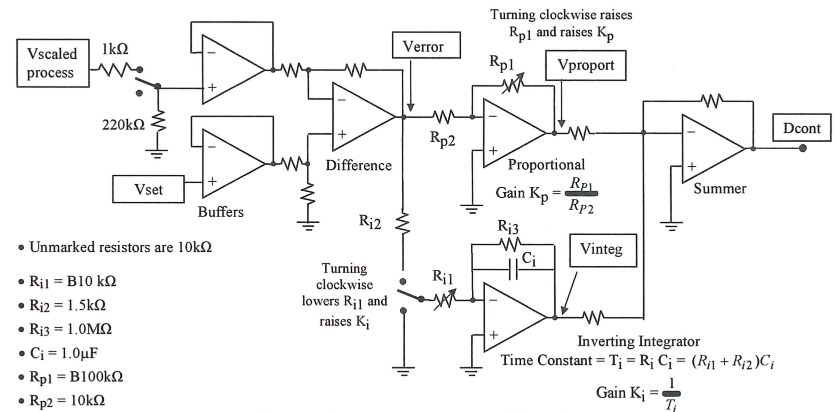


Figure 2. Closed Loop Process with PI Controller

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.

Warning, the signal inputs (i.e., + and – inputs on the left-hand side) of any unused op amps on your circuit board must be grounded to prevent overheating and burnout.



- Unmarked resistors are 10kΩ

- R_{i1} = B10 kΩ
- R_{i2} = 1.5kΩ
- R_{i3} = 1.0MΩ
- C_i = 1.0μF
- R_{p1} = B100kΩ
- R_{p2} = 10kΩ

Figure 3. Op Amp Implementation of PI Controller

The Experiment

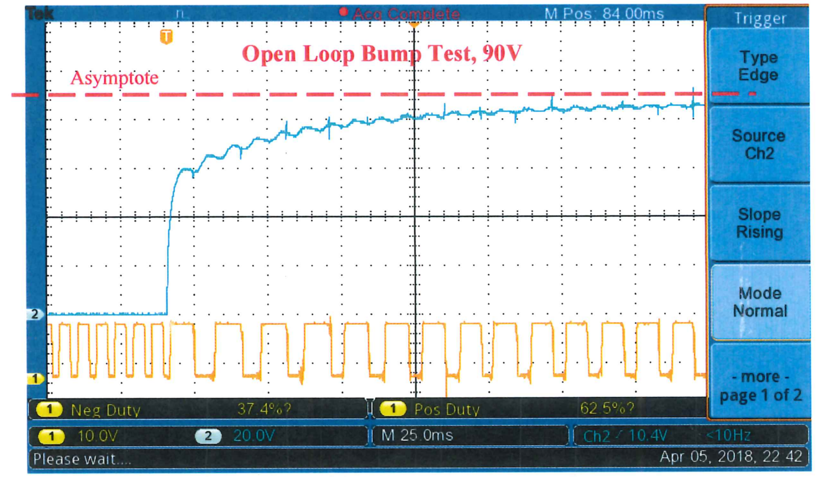
In this experiment, you will power a buck/boost converter with a DBR, and use the controller to hold regulated **90V to a 150W incandescent light bulb**. Operate your buck/boost converter at about **100kHz.**

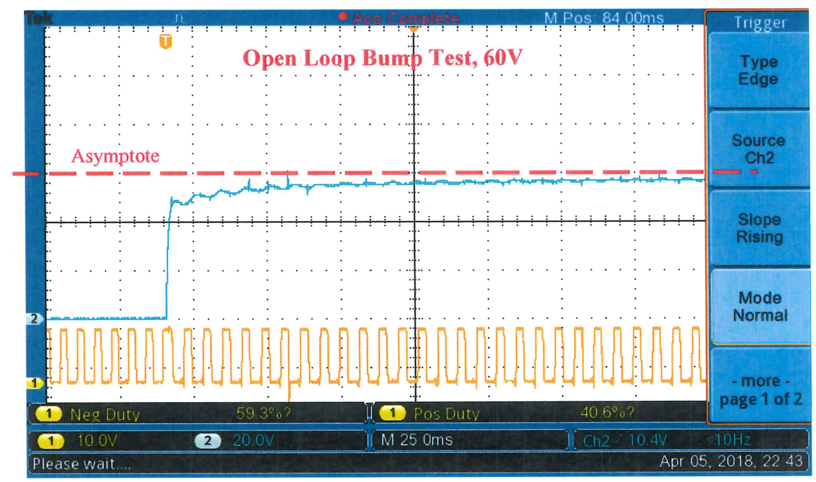
Step 1. Getting Started

- **DO NOT power up the DBR yet**.
- With the manual gain fully clockwise, set the **duty cycle limit to 0.8**. The reason is to prevent the PI controller from rising to the D = 1 condition which would short circuit the MOSFET.
- **Now, power up the DBR**.
- Observe VGS on scope Channel #1 using 5V/division. Roll the D waveform to the bottom of the screen.
- Make sure that your buck converter runs properly with the firing circuit in "manual" mode. It should smoothly change the DC voltage on a 150W incandescent bulb from 40V to 120V.

Step 2. Perform the Open Loop Bump Test to Observe the Time Constant of the Process Being Controlled (i.e., the converter and load).

- Connect Channel #2 probe to view V_{out} across the light bulb's noise reduction capacitor.
- Manually adjust the duty cycle potentiometer until bulb voltage is 90V.
- Toggle off the DBR.
- Set scope time scale to 25msec/division, and voltage scale on Channel 2 to 20V/division.
- Set trigger mode to normal, select Channel 2 for triggering, and adjust the trigger voltage to about 10V.
- Set trigger so that triggering occurs on positive-going change.
- Toggle off the DBR
- Push Run/Stop on the scope (backlight becomes red)
- Push Single
- Toggle on the DBR
- Repeat for 60V.





Step 3. The Set Point

- **DO NOT power up the DBR in this step**.
- Set the SPDT switch of the MOSFET firing circuit to the left position for "External Duty Input."
- **Set Proportional potentiometer fully counterclockwise (minimum K_p)**.
- **Set Integrator potentiometer fully counterclockwise (minimum K_i)**.
- **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.
- Adjust Set Point Potentiometer so that **$V_{set} \approx 1.9V$**. V_{set} is the "target voltage" of the controller, which roughly corresponds to V_{out} = 90V. It will be fine-tuned later.

Step 4. 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 (approx.. −11 volts).
- **SWITCH OFF the Integrator SPDT switch, and make sure the Integrator potentiometer is fully counterclockwise**.

Step 5. Set the Open Loop Gain to Unity

- **Make sure the Integrator and Feedback SPDT switches are off.**
- **Slowly raise** the variac to 120Vac.
- While viewing V_{GS}, **slowly raise** the Proportional K_p Potentiometer until the converter output voltage is 90V ± 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 90V, the K_p potentiometer should be about mid-range.
- **SWITCH OFF the DBR toggle switch.** The duty cycle on the scope should be approximately 0.70.
- **Unplug the wall wart.** Measure R_{p1} between the middle and other prong used. My value was about 50kΩ. The ratio R_{p1} / R_{p2} is the proportional gain needed to yield unit process gain. My gain value for unity was thus 50 / 10 = 5.0. Process K_p will be normalized to this 5.0 unity gain.

Step 6. Close the Feedback Loop, Check for Oscillation Due to K_p

- 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. If there is no sign of oscillation, set the knob half-way.

Step 7. Set K_p

- **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 50kΩ • 0.45 = 23kΩ (about 1/4th knob position).

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

- **Switch ON the Feedback SPDT switch.**
- **Make sure the Integrator SPDT switch is OFF.**
- **Make sure the Integrator potentiometer is fully counterclockwise.**
- **Plug in the wall wart, and SWITCH ON the DBR.** Wait a few seconds.
- **SWITCH ON the Integrator SPDT**. The light bulb will immediately brighten because the controller quickly raises V_{out} to the 90V target value.
- If your output voltage is outside **90V ± 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. If you have no signs of instability, set the integrator knob half way.
- **Unplug the wall wart.**
- If there are signs of instability, measure the net R_i at the onset of instability as follows: Measure the **Integrator** potentiometer resistance by connecting an ohmmeter between the **middle and other prong used**. (I set mine half-way, thus 5kΩ). Then add the series **1.5kΩ** resistor to your reading. The sum is net R_i. (For me, the sum is 6.5kΩ). Thus, with C_i = 1μF, my computed controller stability boundary for $T_i = R_iC_i$ is about 6.5 msec. We want to keep T_i above this value. The purpose of the **1.5kΩ** resistor is to prevent infinite integrator gain during knob movements that create serious burnout oscillations.

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, we deal with a rather significant

120 Hz. ripple, having T =8.3 msec, and must avoid it. Thus, T ≈ 6.6 msec is reasonable. With C_i = 1µF, then **the optimum value for R_i should be around 6.6kΩ.**

- Use an ohmmeter to adjust your R_{i1} = 5.1kΩ to achieve $R_i = R_{i1} + R_{i2}$ = 6.6kΩ. For our case, Ri1 corresponds to a knob position of about 1/2 clockwise.

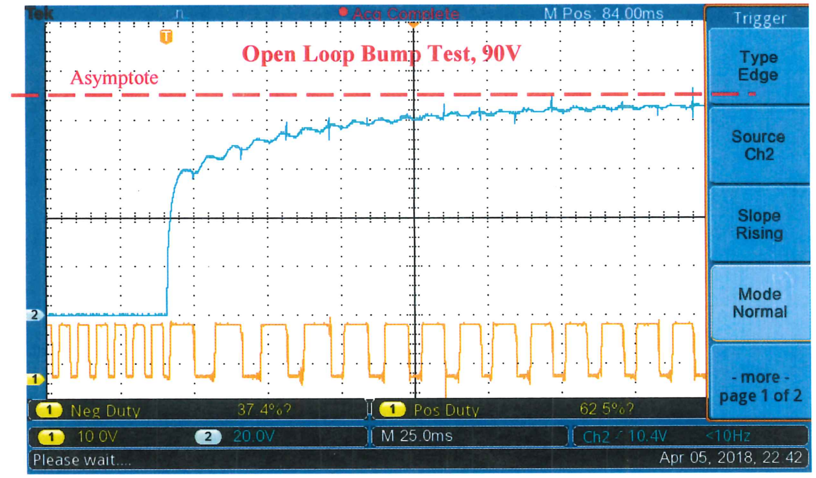
Step 10. Perform the Variac-by-Hand Test

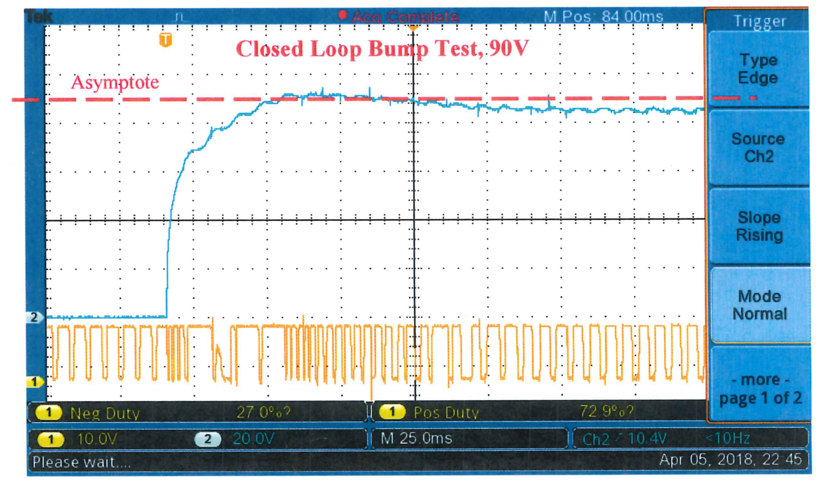
- **Plug in the wall wart, and SWITCH ON the DBR toggle switch**
- While observing V_{GS}, quickly raise and lower the variac voltage. The controller should hold the light bulb brightness constant to the eye, except when the variac voltage is so low that the duty cycle limit is reached. Watch how V_{GS} 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.

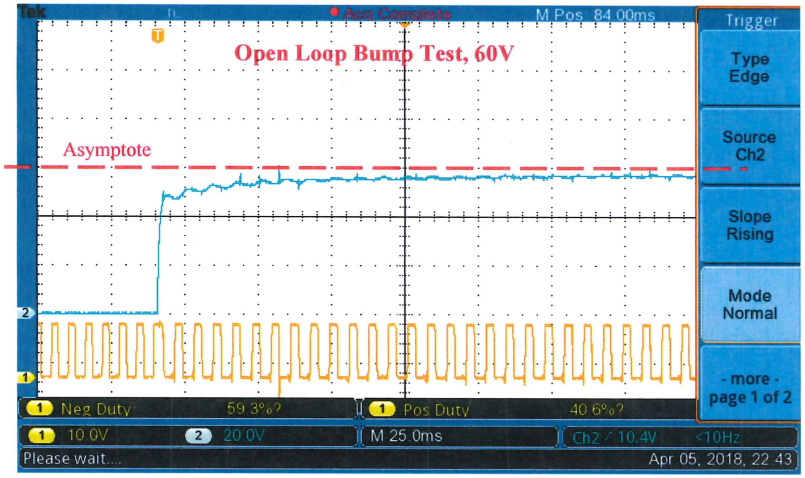
Step 10. Perform the Closed Loop Bump Test, and Vary the Parameters
The test is done the same way as Step 2. The asymptote is the same as Step 2. Step 2 has a classic first-order response. Step 10 has the slight overshoot of a modest second-order response.

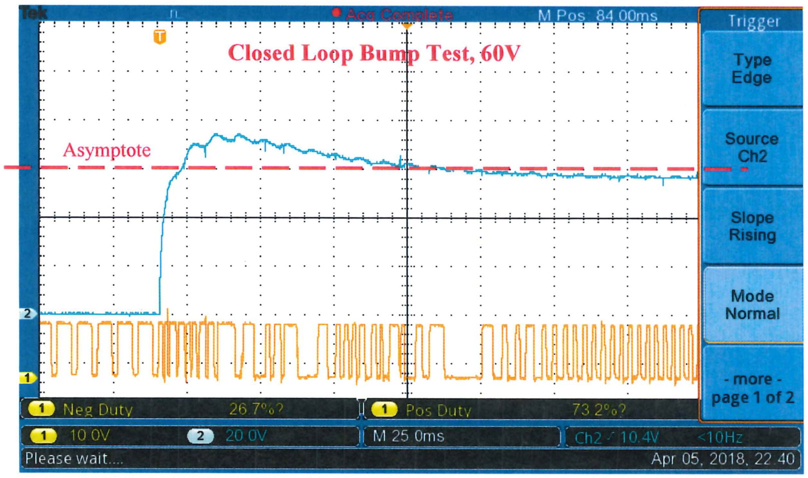
For comparison, both are shown on the following pages.

Second-order response (bottom graph) reaches the target first. The accompanying small level of overshoot is usually not a problem.









Step 11 (Optional, and only if you are using a buck/boost converter), 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?