EE362L, Power Electronics, PI Controller for DC-DC Boost Converter

Version Feb. 20, 2008

Overview

In this lab, you will add an automatic output voltage controller to your boost converter. The controller will hold the output voltage at a set point by adjusting the control input to the PWM modulator. Your output voltage will be 90V. **Please follow the wiring color code during construction. Wire the circuit together with your partner, where one of you checks off each wire and component on the schematic as you go.**

If you built a buck/boost converter, then for the purpose of this experiment, convert it to a boost converter by shorting around C1 and removing L2.

Introduction

A proportional-integral controller (i.e., PI) employed with a feedback loop can take the place of manual adjustment in your DC-DC converter and act much more quickly than is possible “by hand.” Consider the DC-DC converter as “a process,” as shown below. The DC-DC converter includes the converter itself, plus the DC power supply (i.e., transformer/DBR or solar). In the open loop mode, as you used previously, you manually adjusted the PWM control input (to pin 3) via a potentiometer over the range of 0 to 3.5V, where 0V yielded D = 0.0, and 3.5V yielded D = 1.0. The process is nonlinear because D is proportional to V_{pwm}, but V_{out} is nonlinear with D.

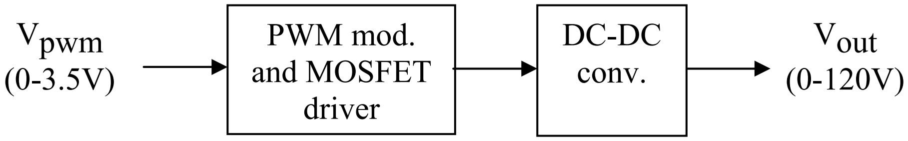


Figure 1. Block Diagram of the Open Loop DC-DC Converter “Process”

To automate the control process, the “feedback loop” is closed, producing an error signal (+ or –). The PI controller acts upon the error with parallel proportional and integral responses in an attempt to drive the error to zero. When αV_{out} equals V_{set}, then the error is zero. The α , via a resistor divider, scales V_{out} to about 1.3V in magnitude so that it can be used with the op-amp implementation of the controller.

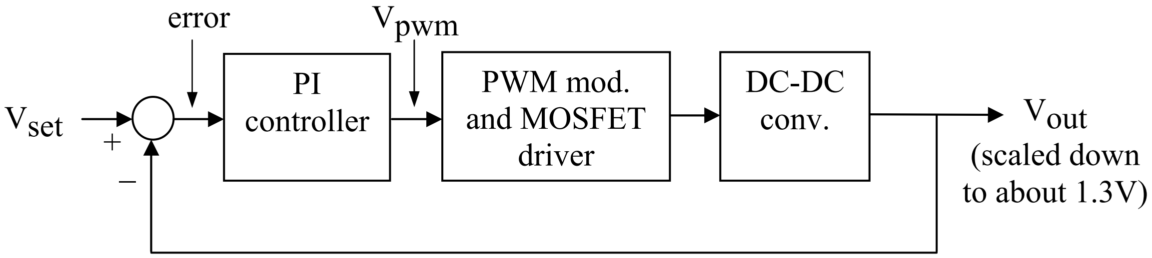
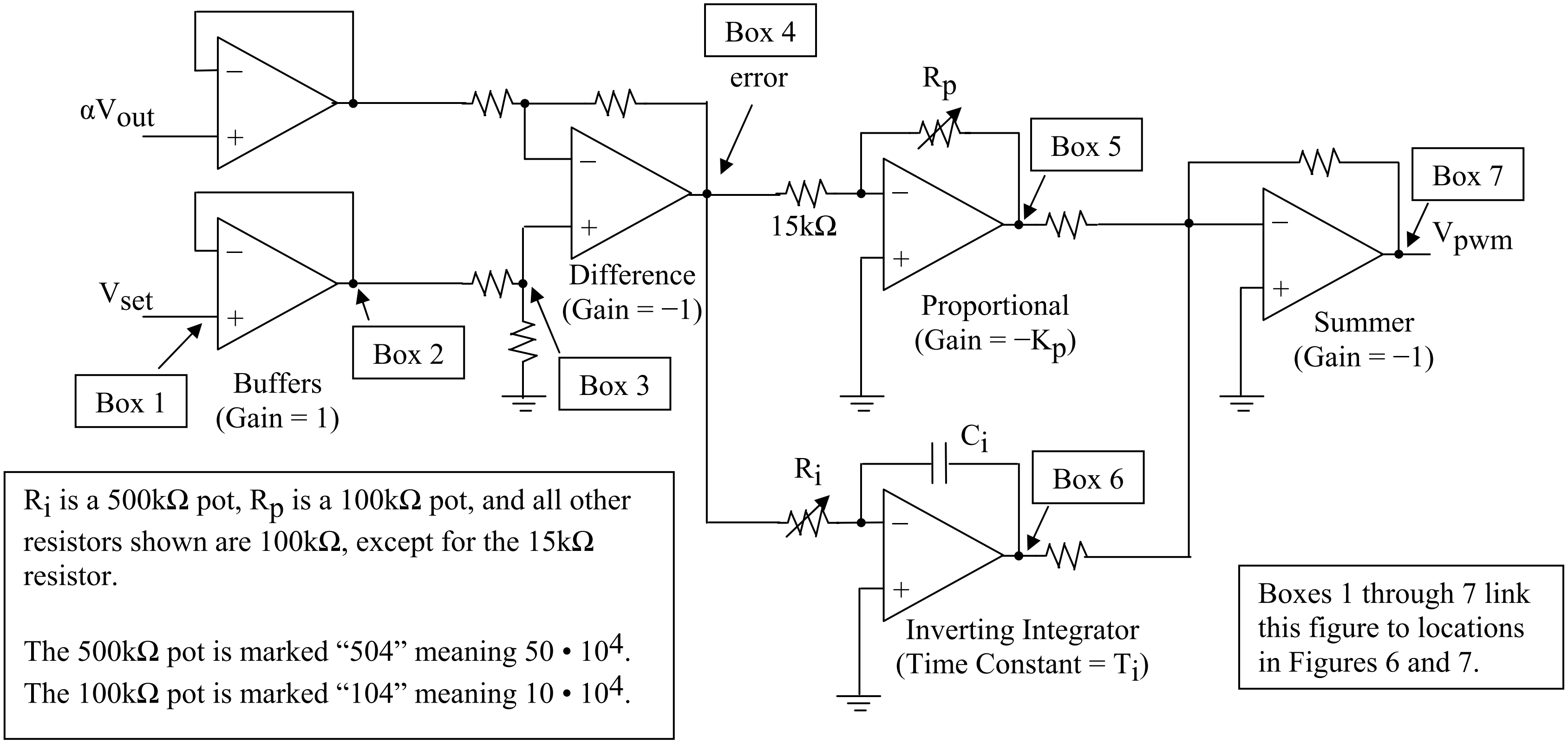


Figure 2. Block Diagram with Feedback Loop and PI Controller

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, two as summers, one for proportional gain, and one as an integrator. Since the op-amp chips that you will use are duals, three op-amp chips are required to implement the PI controller.



R_i is a 500kΩ pot, R_p is a 100kΩ pot, and all other resistors shown are 100kΩ, except for the 15kΩ resistor.

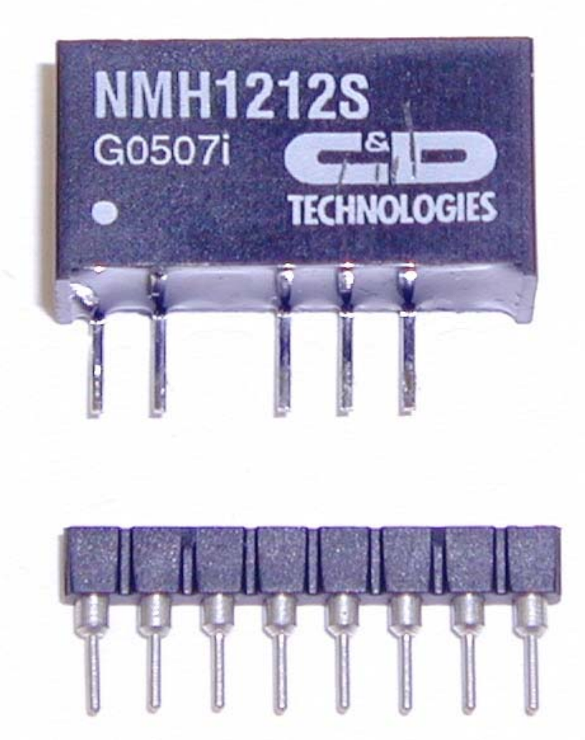
The 500kΩ pot is marked "504" meaning 50 • 10^4.
The 100kΩ pot is marked "104" meaning 10 • 10^4.

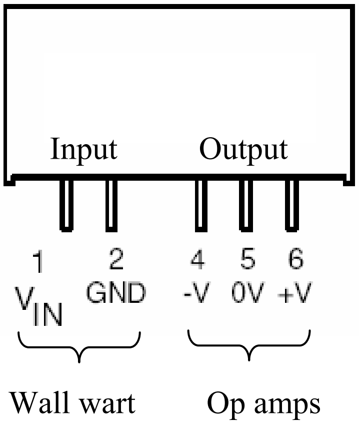
Boxes 1 through 7 link this figure to locations in Figures 6 and 7.

Figure 3. Op Amp Implementation of PI Controller
(Note – net gain K_p is unity when, in the open loop condition and with the integrator disabled, V_{pwm} is at the desired value)

The Circuit

The op amp implementation of Figure 3 is expanded with component values and connection details in Figure 4. The op amps will be powered by a 2W dual output DC-DC converter chip, 12Vdc input, isolated ±12Vdc outputs. Details for the dual output converter and its socket are shown below.





Notes for the above converter chip – connect the ground of the wall wart (pin 2) to the reference of the output (pin 5). **Do not connect the wall wart 12V (pin 1) to the converter chip +12V (pin 6). Doing so will make the converter chip try to regulate the wall wart.**

When energizing your circuit, check the +12V and −12V outputs to make sure they are OK. Low voltages indicate a short circuit in your wiring, which can burn out the chip in a few minutes.

The Experiment

Part 1. Retrofit MOSFET Firing Circuit with the PI Controller Electronics

1. Modify the MOSFET firing circuit according to Figure 5. With the 1800Ω fixed resistor, the frequency of operation should be approximately 90kHz.
2. Add the circuit in Figure 4 to the 6” protoboard. **Do not yet apply wall wart power.** Connect the ground of the firing circuit to the ground of the PI controller. The 100kΩ feedback resistor (R1 in Figure 4) should be attached directly to the converter output, with a blue wire then run from R1 to the 6” protoboard. **Do not put R1 on the protoboard – that would bring high voltage to the protoboard! Do not yet energize the converter with a DBR.**

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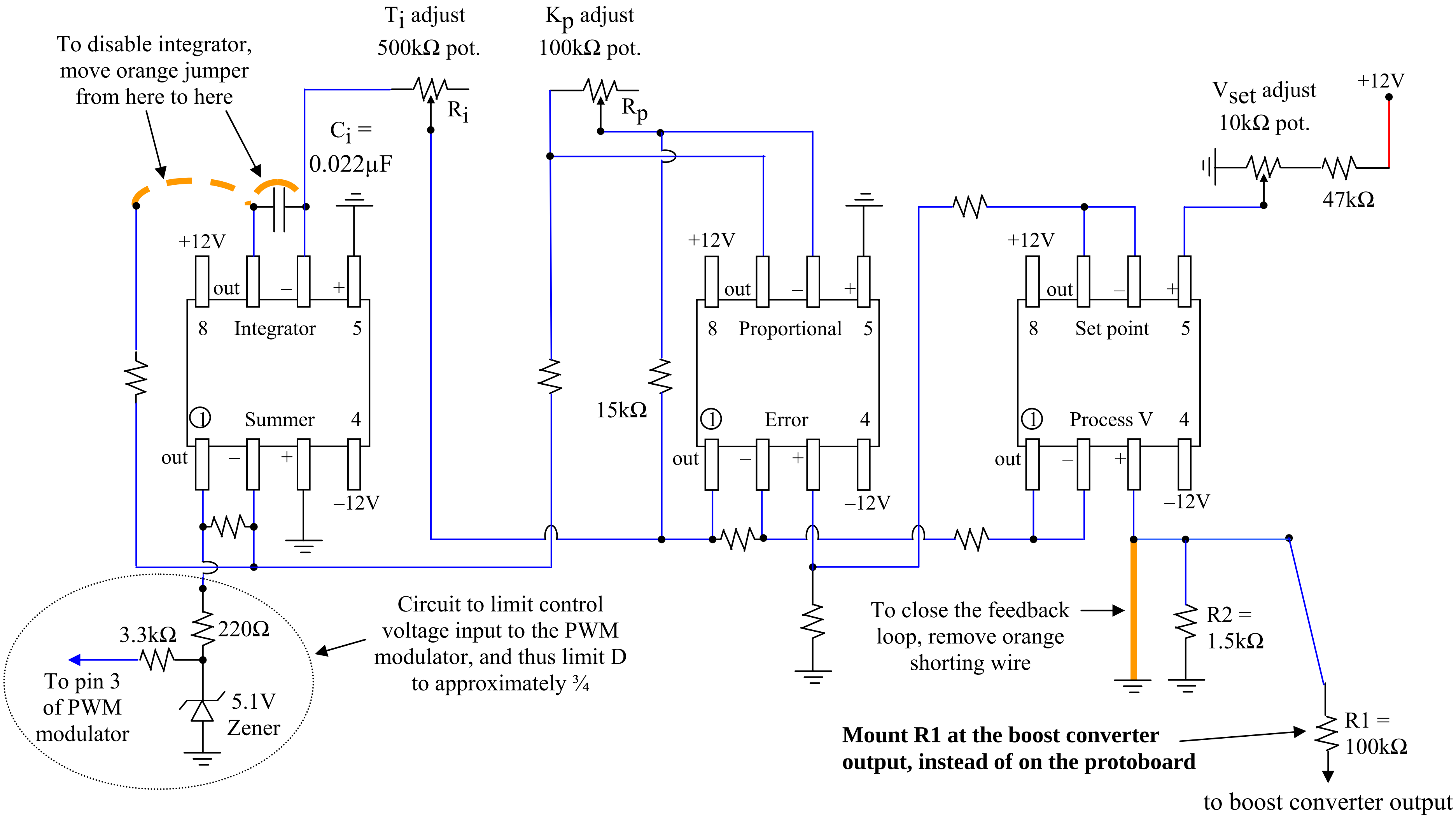

Figure 4. Circuit Layout for PI Controller

(Note – unless otherwise shown, all fixed resistors are 100kΩ, 5% tolerance (or better). Also, the +12V and –12V come from a DC-DC converter chip. Use green wire for ground connections, red wire for +12V connections, violet wire for –12V connections, orange wire for integrator jumper and feedback shorting wire, and blue wire for all other)

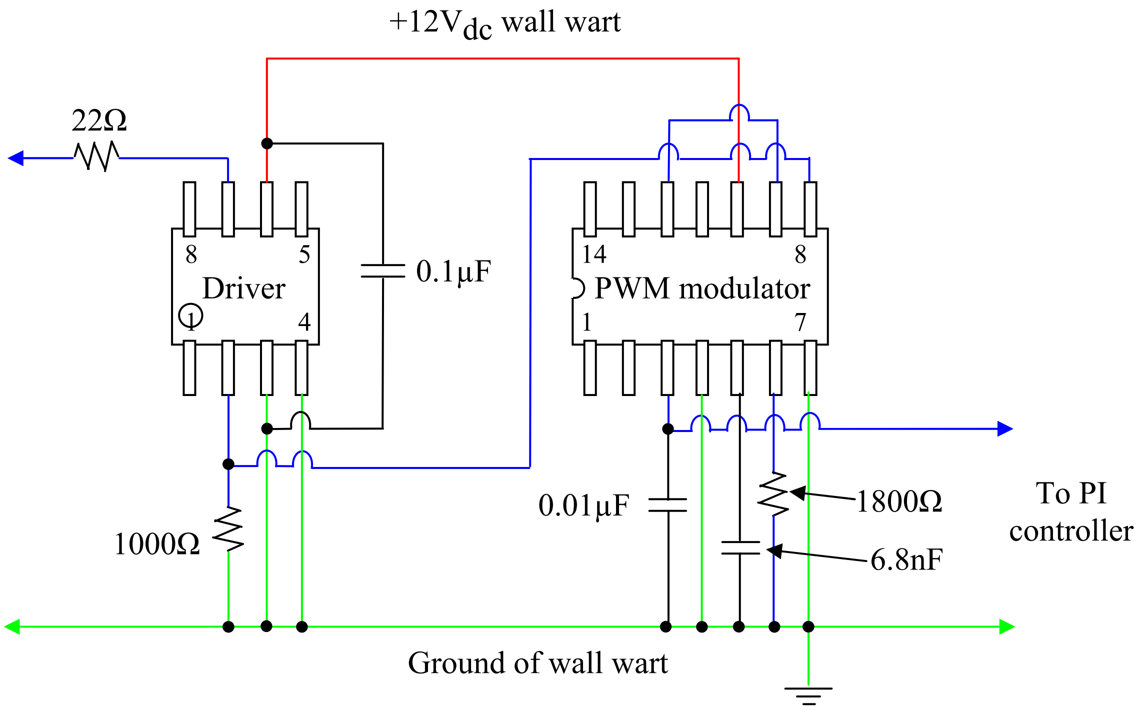

Figure 5. Modified MOSFET Firing Circuit

3. Disable the integrator by **moving the integrator jumper** as shown in Figure 4.
4. Open the feedback loop by **connecting the feedback shorting wire** shown in Figure 4.
5. Add the DC-DC converter chip to provide ±12V (see pin layout on Page 3).
6. Perform the power supply wiring continuity check as follows. **With the wall wart disconnected**, use a multimeter to

   - Confirm that the ground terminal of the wall wart **is connected to** the 0V output pin of the DC converter chip.
   - Confirm that the 12V wall wart output terminal **is isolated from** the +12V output pin of the DC converter chip.

7. Perform the following DC converter chip test as follows. **Connect the wall wart** so that the DC converter chip is powering your circuit. Then,

   - Check the +12V and −12V output voltages of the DC converter chip. If either drops more than 0.5V from nominal, then your circuit is overloading the chip. In that case, you likely have a wiring short circuit, other wiring problem, or possibly a failed component. Unplug the wall wart, debug, and fix the problem before proceeding. Overloading the DC converter chip will cause it to overheat and fail.
   - Make sure that each chip is receiving the proper +12V and −12V supply voltages. Do this using multimeter measurements directly at the appropriate pins on the chips.

8. Using a multimeter, with ground as the reference, adjust the V_{set} potentiometer in Figure 4 so that $V_{set} = \frac{R2}{R1+R2} \bullet V_{target}$, where V_{target} is the desired converter output voltage (i.e., a target of 90V will require $V_{set} \approx 1.3$V)
9. Visually adjust R_p in Figure 4 to mid-range. Then, take and compare voltage measurements to those shown in Boxes 1 – 4 of Figure 6 (Check-Out Sheet #1). Your voltage readings should match within one or two tenths of a volt. Next, using an oscilloscope, adjust R_p to obtain D = 0.50. Then, take and compare voltage measurements to those shown in Boxes 5 – 9 of Figure 6.
10. Raise R_p to full range. Then, take and compare voltage measurements to those shown in Boxes 5 – 9 of Figure 7 (Check-Out Sheet #2). Measure D on an oscilloscope. As shown in Figure 7, D should be approximately 0.80. When finished, lower R_p so that D is again 0.50.

If you have any significant readings from those in Figures 6 and 7, see Dr. Kwasinski or the TAs before proceeding.

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Voltage measurements are made with respect to ground

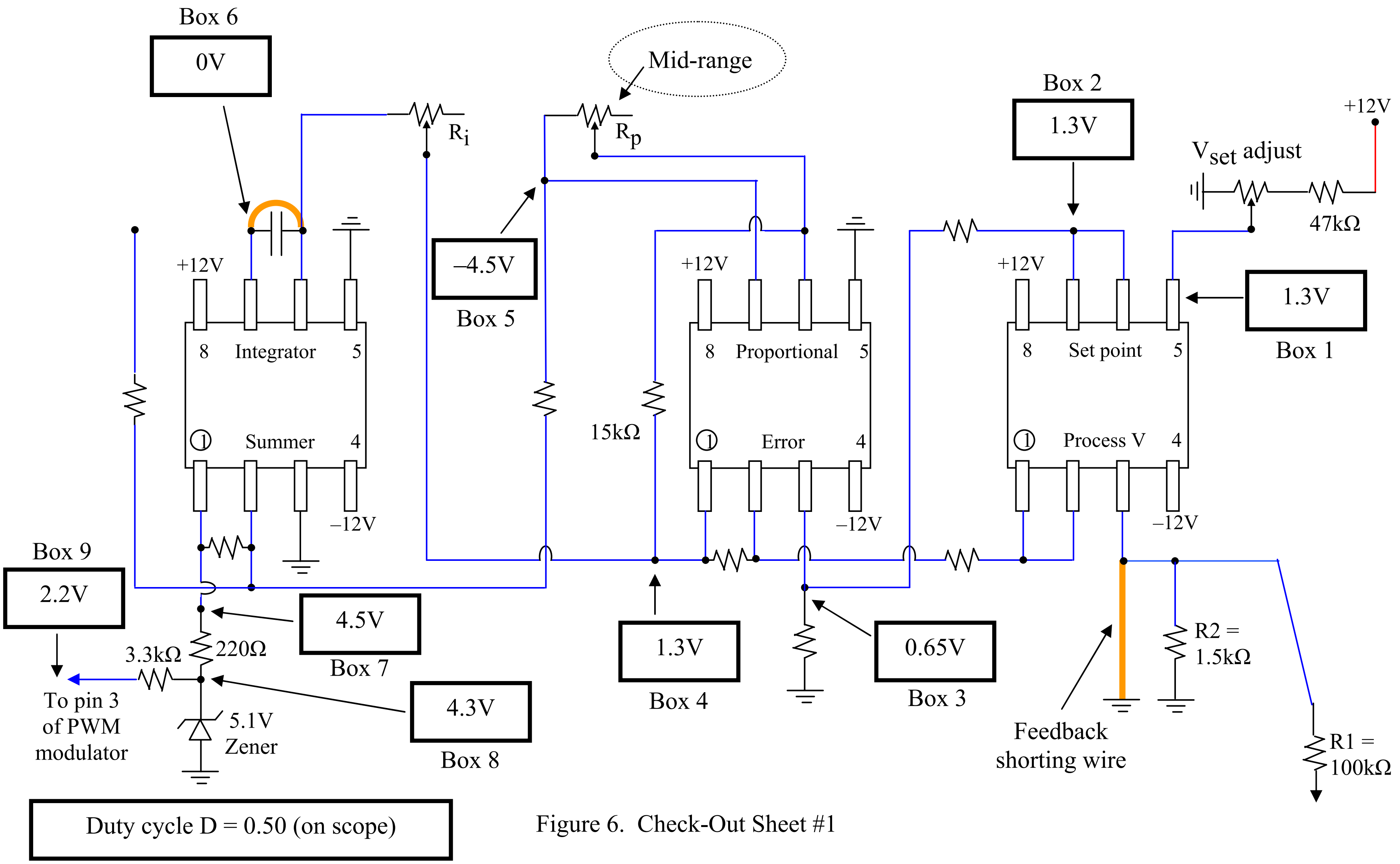

Figure 6. Check-Out Sheet #1

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Voltage measurements are made with respect to ground

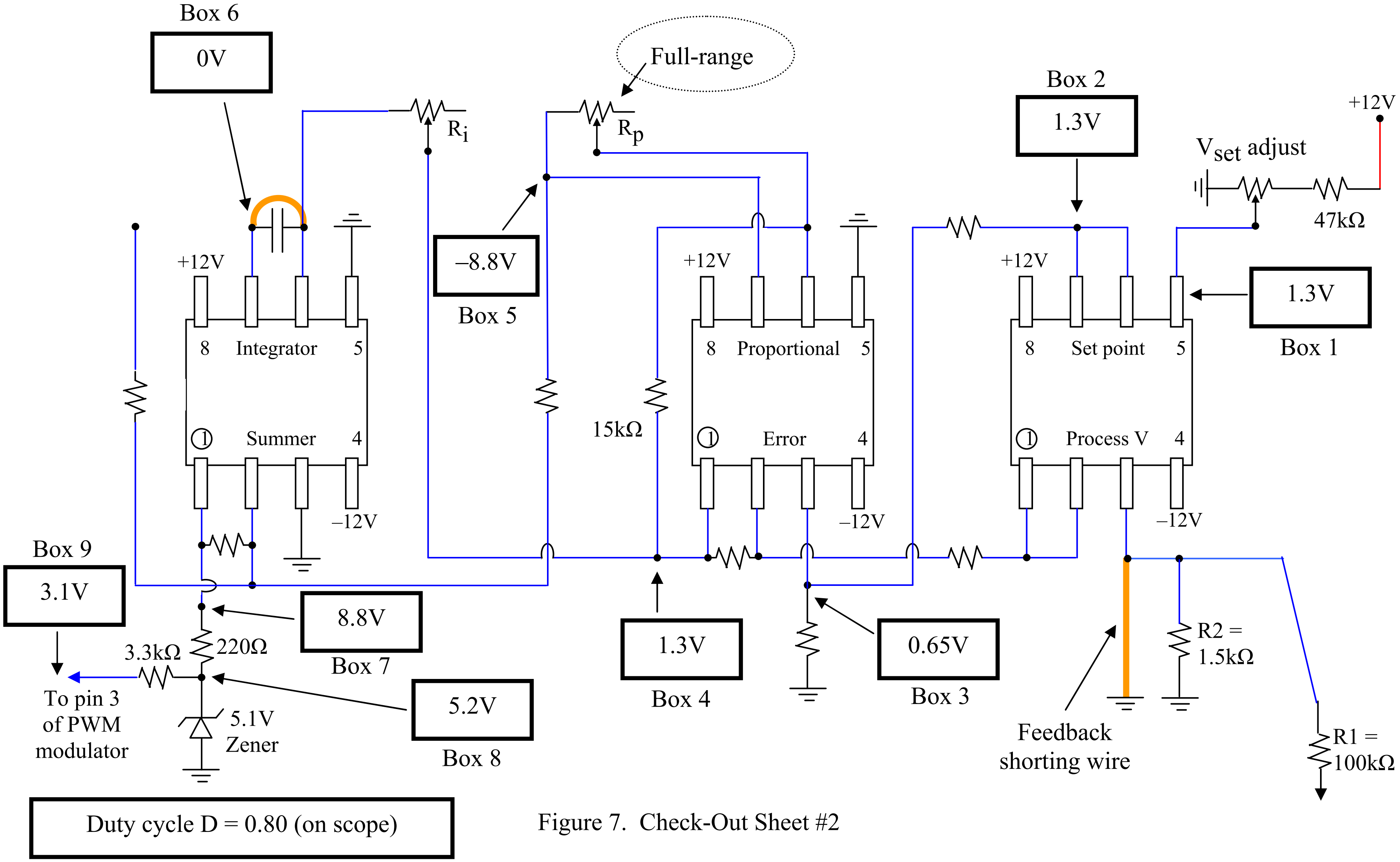


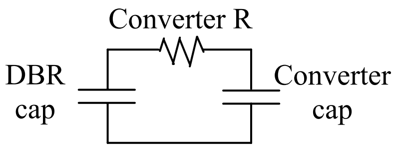
Figure 7. Check-Out Sheet #2

Part 2. Operate the Boost Converter in the Open Loop Mode

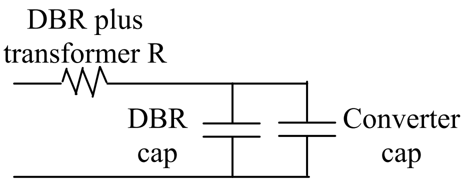
11. Unplug the wall wart. Connect the MOSFET firing circuit with PI controller to a boost converter. Bring a blue wire from the 100kΩ load feedback resistor R1 (in Figure 4) to the PI controller. The feedback shorting wire remains in place.
12. Obtain a 150W light bulb, and confirm with an ohmmeter that it is not burned out. Connect the 150W light bulb to the converter as a load.
13. Plug in your wall wart. Connect a variac through a 25V transformer to a DBR. Then, use the variac to **gradually raise** V_{dc} converter input voltage to 35V. The 150W light bulb should brighten as your raise the variac. With 35V input, measure V_{out} and D. Compare ratio V_{out}/V_{in} to theory.
14. Now, set the net open loop gain to unity by slowly adjusting R_p until V_{out} is 90V. D should be approximately 0.62. Turn off the DBR. Take voltage measurements for points corresponding to Box 4 and Box 5 in Figure 6. The gain of the proportional op amp is the quotient V_{Box5} / V_{Box4}. Define this quotient as KP1. KP1 corresponds to an open loop gain of unity, and it will be used in a later step.

Part 3. Perform the Open Loop Bump Test

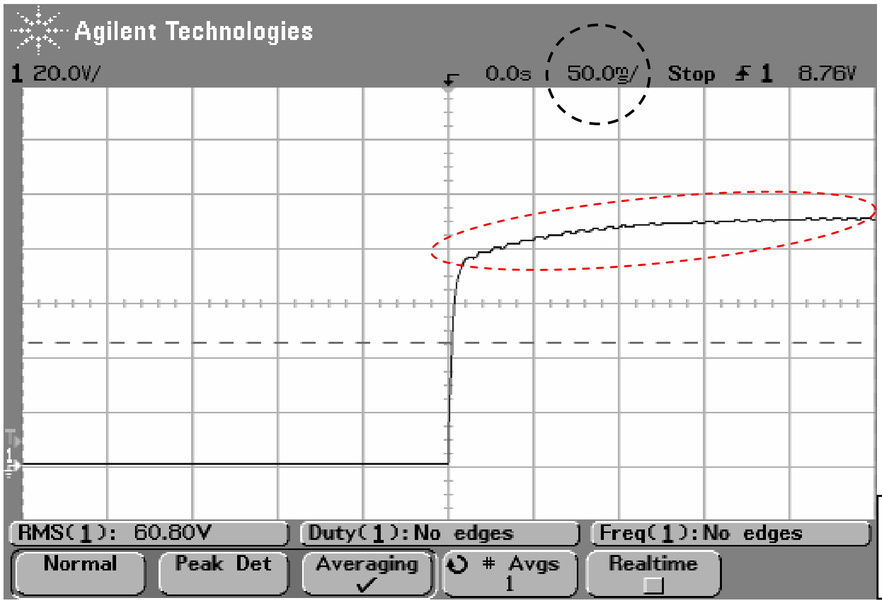
15. Perform a open loop bump tests to measure the open loop time constants of your “process.” The steps are
    - turn off the DBR output switch.
    - connect channel 1 probe to V_{out}.
    - set time scale to 50msec/division, and voltage scale to 20V/division.
    - select averaging, with 1 cycle.
    - set trigger mode to normal, and adjust the trigger voltage to about 5V.
    - set trigger so that triggering occurs on positive-going change.
    - press “single” to freeze the screen on the next trigger. Then, switch on the DBR output switch and capture the open loop response of V_{out}. **Save a screen snapshot for your report.** Upon careful examination of the saved screen snapshot, using both 50 and 5 msec/division scales on the scope, two time constants can be observed in the response. The slow one, in Figure 8, is due to the dynamics of the transformer and DBR. The fast one, in Figure 9, is due to the dynamics of the converter. The two-time constant process is often observed when switching large capacitors in power systems and is explained by the concept of “charge balancing” as follows: for the first few msec, the DBR capacitor and equivalent converter capacitor (reflected through the converter duty cycle switching), together with 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.



Fast time constant – two series capacitors, acting in series with converter resistance

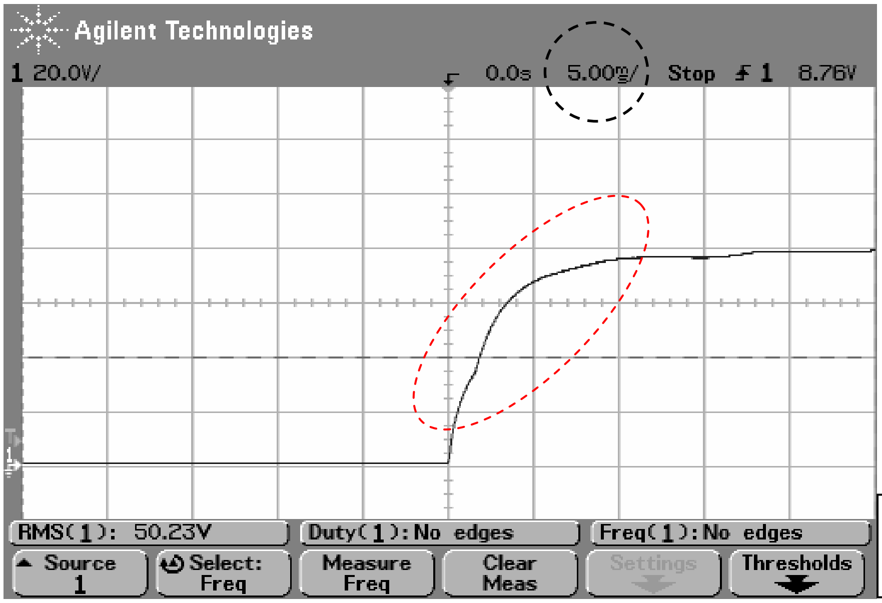


Slow time constant. two parallel capacitors, acting in series with DBR plus transformer resistance



Save screen snapshot #1

Figure 8. The Slow Time Constant of V_{out} during the Open Loop Bump Test



Save screen snapshot #2

Figure 9. The Fast Time Constant of V_{out} during the Open Loop Bump Test (this is a 5msec/div scale zoom-in of Figure 8)

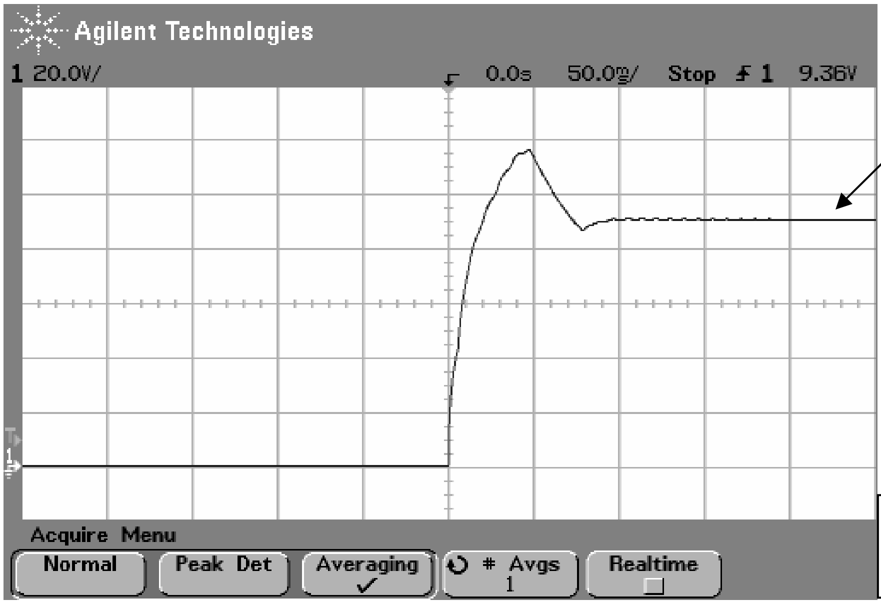
- use the response to estimate the fast time constant T of the converter (note - T is the time required to rise to 63% of the fast asymptote) – it should be approximately 3msec, corresponding to the RC product of C_p (the converter output capacitor), and converter resistance $R = -\frac{\partial V}{\partial I}$ (i.e., a few ohms of Thevenin equivalent resistance).

Part 4. Tune the PI Controller and Close the Loop

16. Adjust $T_i = R_i C_i$ so that it is approximately 0.8T (i.e., with T ≈ 3msec from Part 3, and given C_i = 0.022μF, then R_i should be about 136kΩ). Do this by setting the R_i 500kΩ potentiometer to about one-fourth of its full range.
17. Close the feedback loop by **removing the feedback grounding wire**. Note - the light bulb will dim because V_{out} in Figure 2 will subtract from V_{set} and reduce the error voltage that feeds into the proportional control. Expect V_{out} to drop to about 40V.
18. Set the trigger mode to auto-level. View V_{out} on the oscilloscope, press "run" for continuous triggering, no averaging, and set the time scale to 1msec/division.
19. Sweep R_p through its range, from max to min. Then, starting at the max value of R_p, lower R_p until oscillation ceases or, at least, is small. Note - R_p should be about one-half to two-thirds of its full range. Now, reduce R_p to about 1/2 of that value. Turn off the DBR. Take voltage measurements for points corresponding to Box 4 and Box 5 in Figure 6. The new gain of the proportional op amp is the quotient V_{Box5} / V_{Box4}. Define this quotient as KP2. Gain K_p in (A8) is now the ratio of KP2 to the previous KP1 . Expect a value of about one-third.
20. Enable the integrator by **moving the integrator jumper.** The lights will brighten because the integrator output adds a signal to the summer to drive the error to zero (and V_{out} to the target value).
21. Re-adjust the V_{set} potentiometer slightly to achieve an output voltage of 90V.

Part 5. Perform the Closed Loop Bump Test

22. Perform the bump test as before, but with the converter operating in closed loop.



Notice that most of the 120Hz ripple is gone

Save screen snapshot #3

Figure 10. V_{out} during the Closed Loop Bump Test

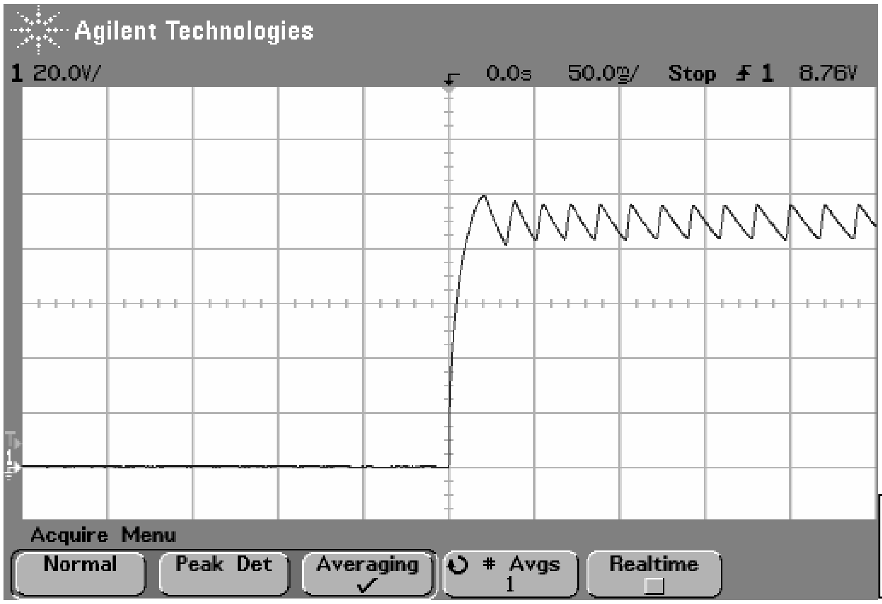
Part 6. Observe Steady-State Voltage Regulation

23. While viewing V_{GS} on the oscilloscope with continuous triggering, viewing V_{out} with a multimeter, and observing the light intensity of the headlamps, vary your variac control knob quickly in both directions. Comment on the ability of the PI controller to hold V_{out} steady. The output should hold steady, within 0.5V, except when the variac voltage drops below 70V (where the duty cycle limiter takes affect).

Part 7. Observe Sensitivity to Tuning Parameters

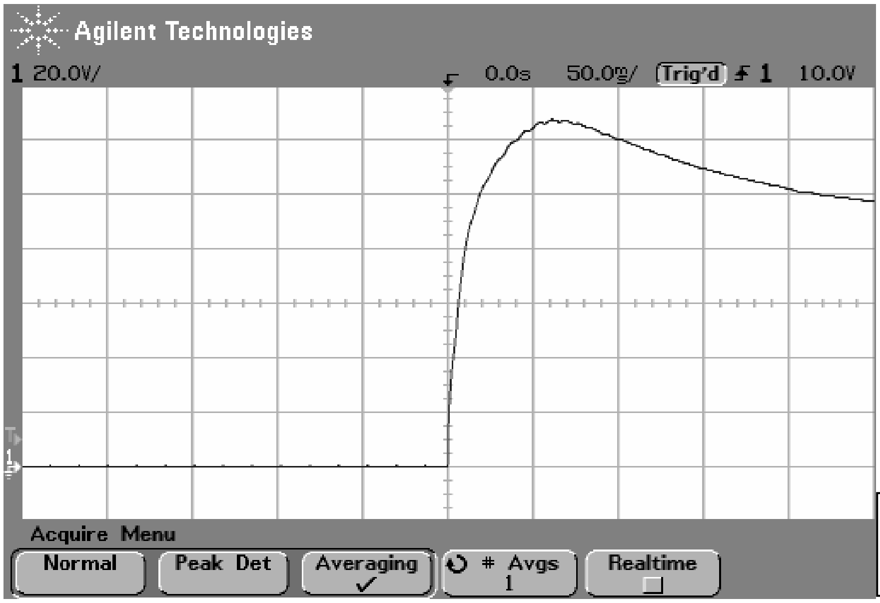
24. Experiment by adjusting T_i and K_p and repeating the closed loop bump test as follows:
    - Lower R_p to minimum. Then, lower R_i until the point of oscillation, and then raise R_i slightly. This situation represents mostly integral control. Repeat the closed loop bump test.
    - Raise R_i to maximum, and then raise R_p to maximum. This situation represents mostly proportional control. Repeat the closed loop bump test.

Observe the effect on overshoot, damping, and ripple. Sluggishness in the transient response indicates dominant proportional control. Too much ringing indicates dominant integral control. A proper balance is preferred. Comment in your report on the effect that variations in T_i and K_p have on controller performance.



Save screen snapshot #4

Figure 11. Closed Loop Response with Mostly Integral Control (ringing)



Save screen snapshot #5

Figure 12. Closed Loop Response with Mostly Proportional Control (sluggish)

Parts List

- Three op amps (dual): Texas Instruments TLE2072CP (Newark #08F9176, or Mouser #595-TLE2072CP)
- ¼W resistors:
  one 220Ω (in student parts bin),
  two 1kΩ (in student parts bin),
  one 1.5kΩ (in student parts bin),
  one 1.8kΩ (in student parts bin),
  one 3.3kΩ (in student parts bin),
  one 4.7kΩ (in student parts bin),
  one 15kΩ (in student parts bin),
  one 47kΩ (in student parts bin),
  eight 100kΩ (in student parts bin).
- One 0.022µF, 100V ceramic disk capacitor (in student parts bin)
- One 0.01µF, 100V ceramic disk capacitor (in student parts bin)
- Trimmer potentiometers:
  one 10kΩ,
  one 100kΩ, and
  one 500kΩ,
  ½W, 3/8" square single-turn cermet trimmer potentiometers, Bourns, (Mouser 652-3386W-1-103-LF, 652-3386W-1-104-LF, and 652-3386W-1-504-LF, respectively). These are marked 103, 104, and 504 for $10 \bullet 10^3$, $10 \bullet 10^4$, and $50 \bullet 10^4$ ohms, respectively.
- One 5.1V, ½ W Zener diode, Fairchild Semiconductor 1N751A (Mouser #512-1N751A)
- Three DIP sockets for op amps
- 2W dual output DC-DC converter, SIP package, 12Vdc input, isolated ±12Vdc outputs, C&D Technologies NMH1212SC (Mouser #580- NMH1212SC)
- One 8-pin SIP socket for DC-DC converter, Mill-Max 310-93-108-001000 (Mouser #575-193108)
- Protoboard (large), Global Specialties EXP-300 (Newark #17C6898 or Mouser #510-103-1300)
- 1" x 6" piece of wood (approx. 12" long piece)

Extra parts

For the student parts bin and screw cabinet, at least

  - 5 of the 250V MOSFETs (individually bagged)
  - 5 of the 200V, 16A ultrafast rectifiers
  - 5 of the DC jacks
  - 5 of the 5kΩ and 10kΩ audio taper potentiometers
  - 5 of the 5kΩ linear taper potentiometers
  - 5 of the 10kΩ, 100kΩ, and 500kΩ trimmer potentiometers
  - 5 of the PWM modulator chips
  - 5 of the inverting driver chips
  - 5 of the op amps
  - 5 of the Zener diodes

- 5 of the 14-pin sockets
- 5 of the 8-pin DIP sockets
- 5 of the green plugs

For the TA's locker cabinet (in addition to those listed in the course description for the student parts bin) – all of the extra parts listed above, plus those listed for the students parts bin in the course description document, plus two complete parts bags, two wood pieces, two complete took kits, two scope probes, a multimeter, 25 floppy diskettes, and a supply of extra plastic bags.

Plastic bags for parts

- 6"x6", 4mil for small parts
- 8"x10", 6mil for holding everything

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

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

where $G(s)$ is the open loop transfer function (i.e., with feedback loop opened). In our case, $G(s)$ is the product of the three individual transfer functions

$$G(s) = G_{PI}(s) \bullet G_{PWM}(s) \bullet G_{DC-DC}(s) \tag{A2}$$

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 combination PWM modulator, driver, plus DC-DC converter, 1.3V input yields V_{out} (scaled) = 1.3V in steady-state, so the gain of the DC-DC converter here is 1.0. The converter exhibits the classic exponential rise time (i.e., charging capacitor), where C is the DC output capacitor, and R is the Thevenin equivalent $\left(-\frac{\partial V}{\partial I}\right)$ of the DC supply. Thus, the net PWM modulator and converter transfer function is

$$G_{conv}(s) = G_{PWM} \bullet G_{DC-DC}(s) = \frac{1}{1+sT} \ , \tag{A4}$$

where $T = RC$.

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

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

Substituting (A5) into (A1) yields

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

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

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,

$$\omega_n^2 = \frac{1}{TT_i} \ , \tag{A7}$$

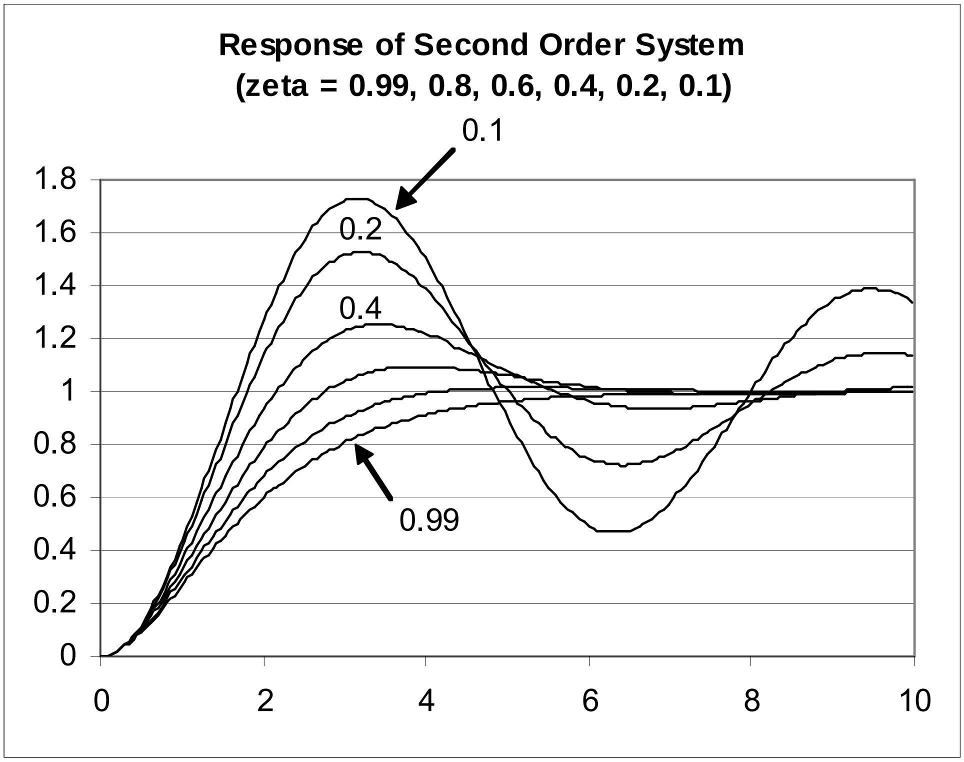
$$2\zeta\omega_n = \frac{1+K_p}{T} \ .$$

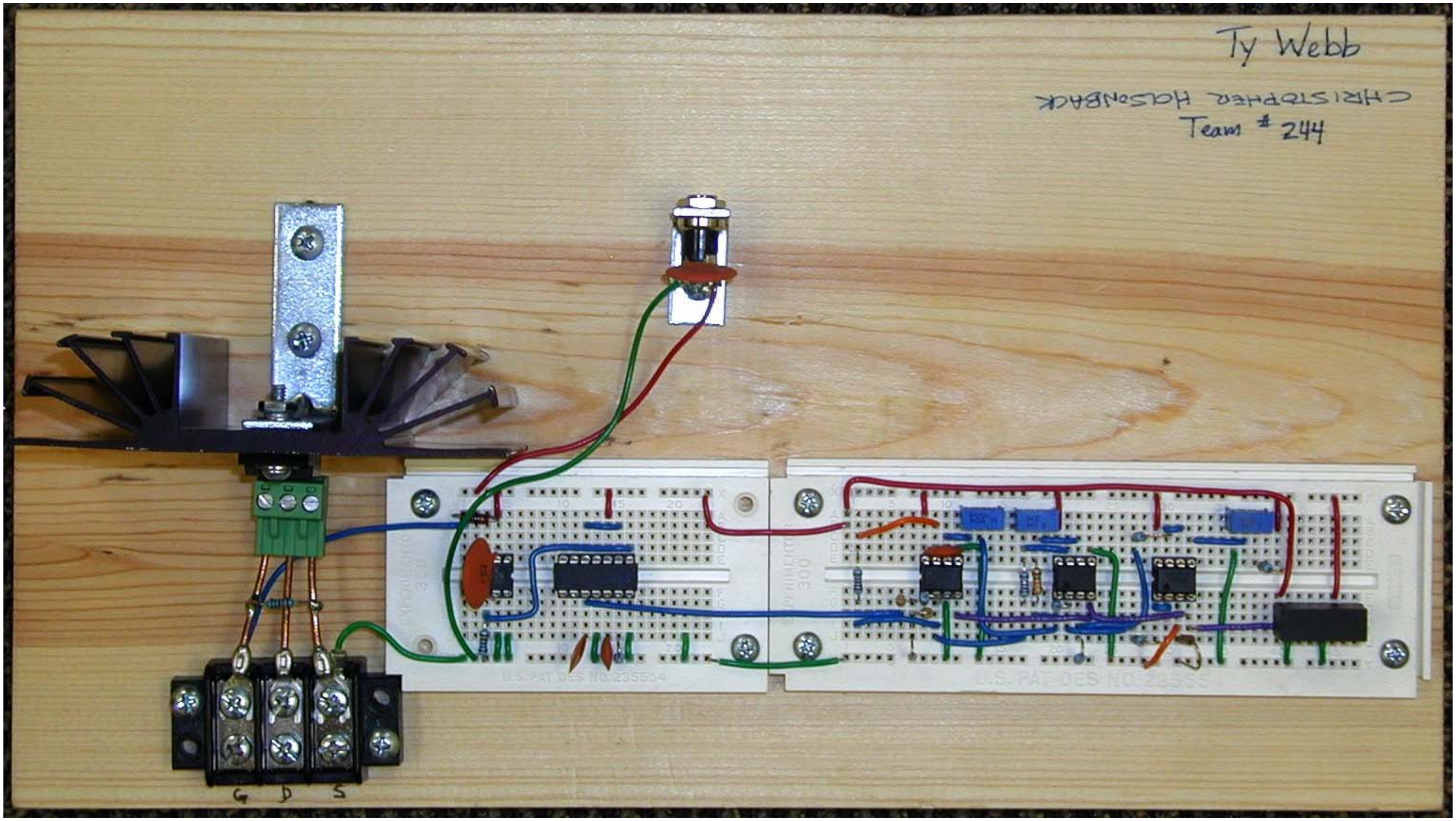
Solving for K_p yields

$$K_p = 2\zeta\omega_n T - 1 = \frac{2\zeta T}{\sqrt{TT_i}} - 1 = 2\zeta\sqrt{\frac{T}{T_i}} - 1 \ . \tag{A8}$$

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.

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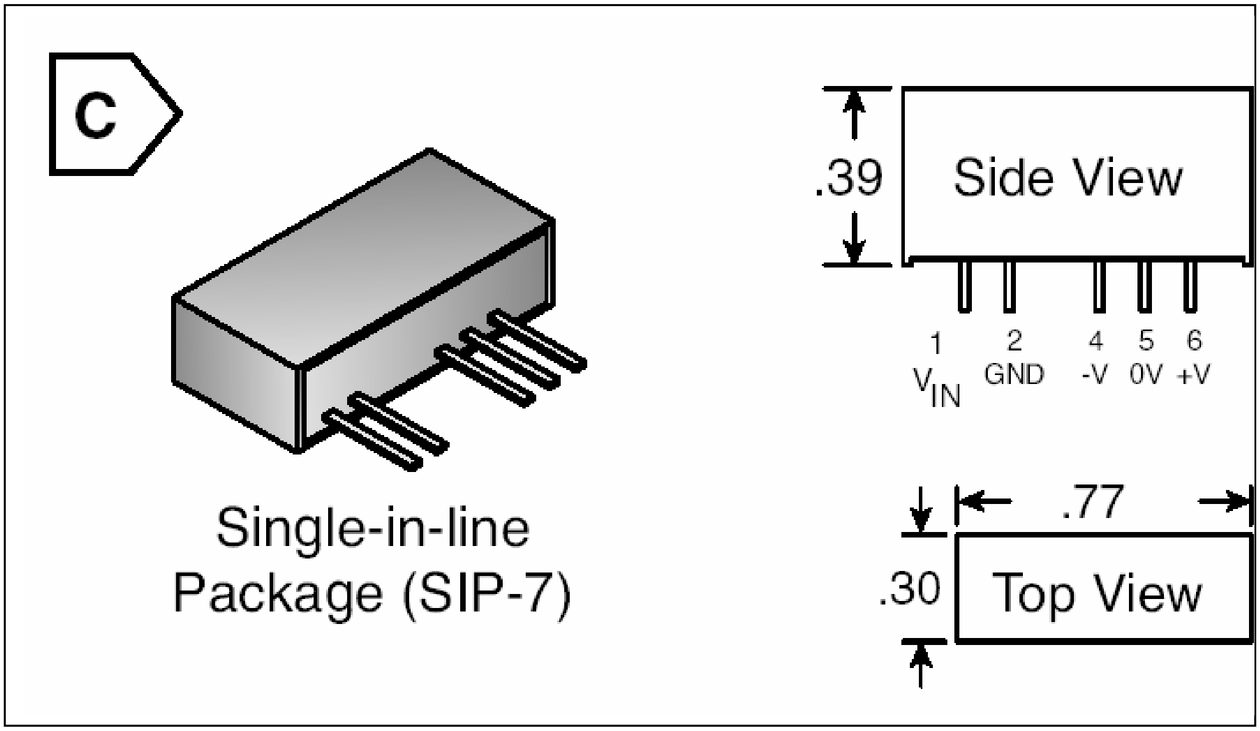
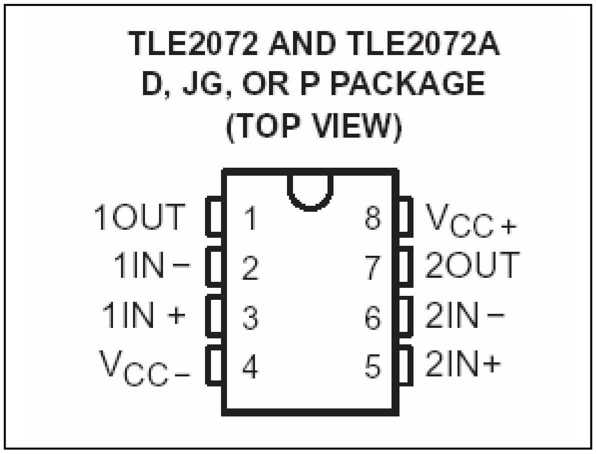
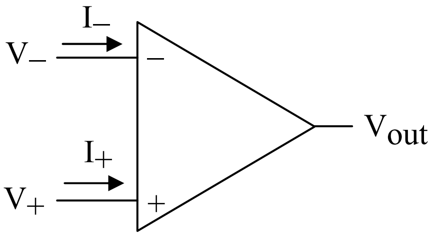
DC-DC Converter Chip



Op Amp



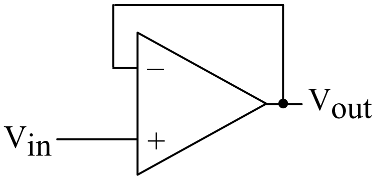
Op Amps



Assumptions for ideal op amp

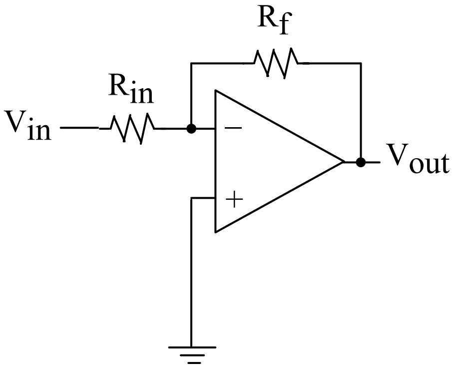
- $V_{out} = K(V_+ - V_-)$, K large (hundreds of thousands, or one million).
- $I_+ = I_- = 0$.
- Voltages are with respect to power supply ground.
- Output current is not limited.

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



$V_{out} = K(V_{in} - V_{out})$, so $V_{out} + KV_{out} = KV_{in}$, so $V_{out}(1+K) = KV_{in}$, so $V_{out} = V_{in} \bullet \dfrac{K}{1+K}$. Since K is large, then $\boxed{V_{out} = V_{in}}$.

Inverting Amplifier (used for proportional control signal)



$V_{out} = K(0 - V_-) = -KV_-$, so $V_- = -\dfrac{V_{out}}{K}$.

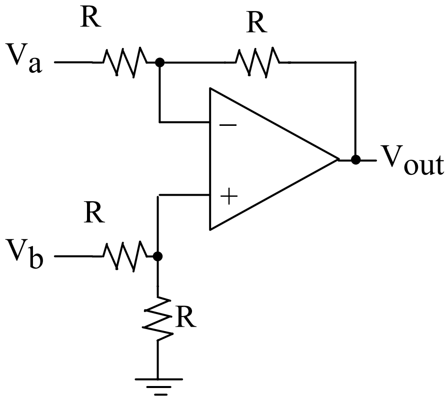
KCL at the – node is $\dfrac{V_- - V_{in}}{R_{in}} + \dfrac{V_- - V_{out}}{R_f} = 0$.

Eliminating V_- yields

$$\frac{-\dfrac{V_{out}}{K} - V_{in}}{R_{in}} + \frac{-\dfrac{V_{out}}{K} - V_{out}}{R_f} = 0 \text{, so}$$

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

Inverting Difference (used for error signal)



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

$$V_- = \frac{V_b}{2} - \frac{V_{out}}{K}.$$

KCL at the – node is $\dfrac{V_- - V_a}{R} + \dfrac{V_- - V_{out}}{R} = 0$, so

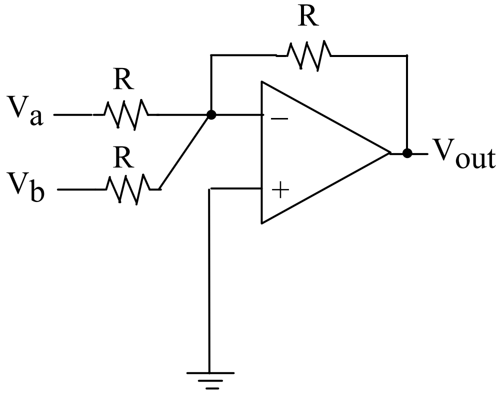
$V_- - V_a + V_- - V_{out} = 0$, yielding $V_- = \dfrac{V_a + V_{out}}{2}$.

Eliminating V_- yields

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

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

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



$V_{out} = K(0 - V_-) = -KV_-$, so $V_- = \dfrac{-V_{out}}{K}$.

KCL at the – node is

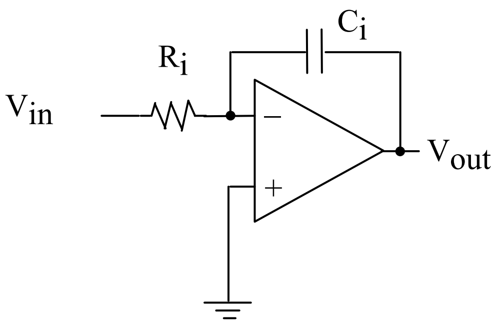
$$\frac{V_- - V_a}{R} + \frac{V_- - V_b}{R} + \frac{V_- - V_{out}}{R} = 0, \text{ so}$$

$$3V_- = V_a + V_b + V_{out}.$$

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

Thus, for large K, $\boxed{V_{out} = -(V_a + V_b)}$

Inverting Integrator (used for integral control signal)



Using phasor analysis, $\tilde{V}_{out} = K(0 - \tilde{V}_{-})$, so

$\tilde{V}_{-} = -\dfrac{\tilde{V}_{out}}{K}$. KCL at the − node is

$$\frac{\tilde{V}_{-} - \tilde{V}_{in}}{R_i} + \frac{\tilde{V}_{-} - \tilde{V}_{out}}{\dfrac{1}{j\omega C}} = 0 .$$

Eliminating $\tilde{V}_{-}$ yields $\dfrac{\dfrac{-\tilde{V}_{out}}{K} - \tilde{V}_{in}}{R_i} + j\omega C\left(\dfrac{-\tilde{V}_{out}}{K} - \tilde{V}_{out}\right) = 0$. Gathering terms yields

$\tilde{V}_{out}\left(\dfrac{-1}{KR_i} - j\omega C\left(\dfrac{1}{K} + 1\right)\right) = \dfrac{\tilde{V}_{in}}{R_i}$, or $\tilde{V}_{out}\left(\dfrac{-1}{K} - j\omega R_i C\left(\dfrac{1}{K} + 1\right)\right) = \tilde{V}_{in}$ For large K, the expression reduces to $\tilde{V}_{out}\left(- j\omega R_i C\right) = \tilde{V}_{in}$, so $\boxed{\tilde{V}_{out} = \dfrac{-\tilde{V}_{in}}{j\omega R_i C}}$ (thus, negative integrator action).

For a given frequency and fixed C, increasing R_i reduces the magnitude of $\tilde{V}_{out}$.