Lab #10: Switching Power Supply Design

Please carefully study H&H, 9.6.4 thru 9.6.10. Also see Canvas Modules. For Saturday, see below.

Part 1:
Design and build a PWM generator that will provide a clean, fixed-frequency, variable duty-cycle rectangular pulse with fast rise and fall times. Select a frequency anywhere from 25 kHz to 30 kHz. Operate on a single bench supply that will be varied from 16 to 28 VDC. For this part of the lab, the output only needs to drive an oscilloscope. The duty-cycle will be controlled by a voltage input derived from a pot, and be smoothly variable from approximately zero to 100%. Design your circuit so that the control-voltage/duty-cycle transfer function is nominally linear. Verify proper operation of the circuit and confirm that the frequency and duty-cycle do **not** change appreciably as the power supply voltage is varied from 16 to 28V, and that the waveform is clean and stable. You may use a 3-terminal "local" regulator if you wish. Record the triangle and pulse waveforms at a few operating points.

With the addition of an open- collector output transistor, you will use this generator in the next part of the lab. You will build a ***buck*** ("step-down" or *forward-mode)* DC to DC converter using the PWM generator, a MOSFET, inductor, diode, filter capacitor, and related components. Note that the power stages of this inverter must be assembled on a PCB-style soldered breadboard to minimize spurious inductance. I suggest you first build the PWM generator on a solderless breadboard and carefully confirm its operation. Then, you can carefully jumper the PWM circuit over to the PCB containing the power components while minimizing inductance due to lead length. However, it would probably be preferable to also transfer the PWM generator components to the solder-style PCB so the entire circuit is on one board. Note, however, that the power supply you build in Part 2 will be open-loop, and that additional components will be required in Part 3 when you close the loop. You will have to monitor inductor current and diode current, so leave small loops that will accommodate the current probe.

Part 2:
Design and build the converter according to the specifications below. Use a P-channel MOSFET along with a simple gate-drive circuit; be careful to accommodate the input voltage range. Modify your circuit in Part 1 as needed to drive the MOSFET. The output will be manually variable via the potentiometer in Part 1. This will be an **open loop, non-regulated power supply**, whose output voltage will be set by manual adjustment of the duty cycle. Be sure that you do not exceed the maximum Vgs rating of the MOSFET!

Specifications:
Vin: 16 to 28 VDC. Vout = variable, 5 to 15 VDC; Adjustable via potentiometer.
Iout = 0.05 to 0.3A
Inductor: 270 uH to 820 uH. An inductor with low series R (<1Ω) is necessary.
Frequency: 25 to 30 KHz.
Diode: 1N5818 or 1N5819 Shottky. MOSFET: IRF9Z24 P-CH. Or equiv.
A heat sink should not be required. Why not?

►Do NOT attempt to use a solderless breadboard for high current sections.
►Use a current probe for the inductor and diode currents; includes small wire loops for the current probe.

Evaluate the operation of the open-loop power supply:
►Note the changes in the inductor current and MOSFET drain-voltage waveforms as you vary V_{in}, V_{out} (by changing the duty-cycle), and the load. ►**Record** for your lab report representative V_{drain}, I_{diode}, and $I_{inductor}$ waveforms for endpoint values of V_{in}, V_{out}, and load (change duty-cycle to set operating point). Show diode and identify reverse recovery spikes on your recorded waveforms.

Change the diode from a fast recovery to a standard recovery device. ►Carefully note and record changes in waveforms. **During recitation, be prepared to demonstrate your circuit and explain waveforms and component selections!!!**

Note that as you change both V_{in} and/or the load, you can manually adjust the duty-cycle to set V_{out}. Since, in the next section, you will close the loop and build a regulated supply with an adjustable 5 to 12V output, ►Determine and record the max and min values of the duty-cycle (DC) that are required to produce this output range as both V_{in} and the load are varied over the specified range (locus of points).

DC_{min}_______________% DC_{max} __________ %

►Calculate the power dissipation of the MOSFET with the duty cycle adjusted to provide the following conditions: Vin = 24VDC; Vout = 5VDC/ 0.3A. Take measurements as needed and show your calculations.
► What is the efficiency of your circuit? How could it be improved?

Part 3(a):
In Part 2, you operated your circuit in open-loop mode. Now, add the necessary components to convert your circuit to a regulated (closed-loop) power supply with a variable output of 5 to 12 volts. Your supply should be stable and provide good line and load regulation (< 1%?) with the use of a simple, proportional feedback loop. **Important**: Carefully observe the waveforms to be sure that there is no oscillation or jitter.

Part 3(b):____
►Measure and record Line Regulation and Load Regulation. Also, measure overall efficiency at Vin = 24VDC; Vout = 5VDC/ 0.3A.

REG_{line} =_________ % Reg_{load} = ___________ % Efficiency___________%

►What would be the dissipation in the pass element of a LINEAR supply under the same operating conditions?

Part 3(c):
►Change to a *standard recovery* diode (1N4000 series) and record the V_{drain}, I_{diode}, and $I_{inductor}$ waveforms and the efficiency when operating at the conditions in 3(b).

Efficiency (std. recov. diode) = _____ %

Part 4:
►Add active current limiting to your power supply to limit I_{out} to about 0.4 A. Remember that this is a switcher and it must remain a switcher, so the current limiting must be accomplished by <u>changing the duty-cycle as needed</u> to reduce the current. Record the inductor-current waveform during an output short-circuit.

Measured $Iout_{sc}$ = ____________ Amp

Will this circuit reliably withstand an instant short circuit at the output?
Prepare a clean, final schematic for the recitation. <u>Be prepared to demo the power supply in Part 4 for the recitation.</u> Also, keep the PWM section built for next week's lab.

For Saturday, provide a schematic of Parts 1, 2, and 3. Also, provide a sketch of the expected I_{drain}, V_{drain}, I_{diode}, V_{diode}, and $I_{inductor}$ waveforms when operating the above circuit with a 24V input and a 5V, 0.3A output.

Comments on Lab 10:

1. Be sure you check the specs regarding the maximum sinking current of the LM339 comparator (or similar part) output.

2. If you choose to use a voltage divider to provide a split supply or reference, you should always bypass the center of the divider so that this point remains fixed under pulse conditions.

3. Be careful to drive the MOSFET so that moderately fast switching speeds result. Keep in mind the high capacitance that appears at the MOSFET gate. However, also be aware that problems can result from switching times that are too fast; these may produce transients and voltage spikes due to parasitic inductance and capacitively coupled conductors. Rise and fall times at the MOSFET gate should probably be on the order of a microsecond or so.

4. Remember: LAYOUT!! The power circuitry <u>must</u> be constructed very tightly, with thought given to lead inductance and resistance. Pay attention to where heavy currents will be flowing and where voltage drops will it occur due to lead resistance and inductance. Make sure that these voltage drops do not cause problems - because they probably will. Use one of the perforated breadboards with solder pads. Uninsulated #18 “bus” wire is available on the rack at the end of the lab and may be used for interconnection.

5. Lead inductance must be minimized by careful layout. First, locate the high current paths and try to keep their loops small. For example, in your circuit the discharging inductor will drive current thru the filter cap and load, thru the ground line, and then back thru the diode. The current in this loop is fairly smooth, but the reverse-recovery current of the diode will produce a large spike. One example of a potential problem is the case where a voltage spike somehow appears at the gate of the MOSFET and causes unexpected oscillation. To minimize voltage drops due to lead inductance, the anode of the diode, the capacitor negative, and the load negative should all be soldered together at a single ground node. A single wire from this point would run to the bench supply negative.

The gate-driver circuit should be connected as close as possible to the MOSFET source. Also, the location of the ground connection from the pulse generator circuit (the emitter of the open-collector transistor) requires some thought. Be VERY careful to connect this to a suitable node.

5. The purpose of Part 2 is for you to get a feel for how the basic buck circuit works, without worrying about the feedback portion. In other words, by manually adjusting the PWM, you can test the power section of the supply over the full operating range (input voltage, output current, and output voltage). You can easily determine, for example, if your inductor is the proper value, estimate efficiency, make sure that you don’t have spurious oscillations, etc. **If the circuit doesn’t work perfectly without the feedback control, it will never work with it.** Of course, it is also much easier to troubleshoot the circuit without the feedback network.

6. Regarding generation of the triangle wave, remember that you do not have to generate a true triangle wave. For example, a sawtooth will work just fine. Even a distorted, or non-linear waveform is acceptable because the nonlinearity is overcome by the feedback loop. However, the *transfer function*, or overall gain of the circuit’s error amplifier, will vary as the threshold moves up and down and passes through sections of the waveform with varying slope. Nevertheless, if the nonlinearity is not too extreme, this shouldn’t be a problem.

Therefore, you don't have to use the traditional, op-amp/comparator approach that incorporates a true integrator to generate the waveform. I have mentioned that you can use a single, inverting Schmitt-trigger CMOS gate or comparator in a simple RC circuit to generate a pseudo triangle-wave. This approach works well with a single supply. Since comparators and gates are faster than op amps, is also easy to generate the relatively high frequency waveform that you need.

As the error amplifier output is compared to the triangle waveform, changes in the error-amplifier output produce changes in duty cycle; this, combined with the gain of the error amplifier, represents the overall proportional gain of the feedback loop. Remember that your error-amplifier gain should **not** be too high; if it is, the circuit will be unstable.

With what you learned in Part 2 of the lab, you can roughly estimate how much gain you need to provide a given degree of voltage regulation. This is because it is easy to approximate how much change in the duty cycle is necessary to produce a given change in output voltage. For example, you might find that a swing of 1V at the error-amplifier output will change the output voltage 10 volts. Therefore, if your error-amplifier has a gain on the order of 10, then the composite proportional gain is about 100 and change of 0.06 V (1%) will probably produce enough of a change at the PWM threshold voltage to result in a suitable correction of the duty cycle.

Remember that the specific gain of the error amplifier is not critical; what is important is that you get reasonable line and load voltage regulation (<1 %?) and no oscillation.

7. IMPORTANT: be sure you do not exceed the maximum VGS -even for a microsecond. Please check the data sheet!! If you find a problem, it may not be too hard to solve; try to think of a simple solution,

8. You may find that your power supply output has spikes on it; these are most likely produced by the fast-switching MOSFET. Keeping lead lengths short and switching times slow are your best defense against spikes that appear due to radiation. Also note that scope probes can easily pick up these radiated spikes (especially our cheap ones). Indeed, it's helpful to determine if the glitch is really there. You can check to see if a "ghost" spike is being picked up by the scope probe by disconnecting it completely from the circuit and connecting the clip on the pigtail directly to the scope probe. Obviously, the scope probe is shorted out and shouldn't be picking up anything, but you may see radiated impulses.

   Placement of the scope probe can also affect how large a spike appears to be. If you are checking the output waveform, for example, it is important to place the probe and its ground pigtail directly across the output capacitor and as close as possible to it.

   You can often determine the source of a spike by using 2 traces to see if the spike is synchronized with the fall or rise time of the MOSFET.

   Increasing the size of the output filter capacitor may not greatly reduce output ripple and spikes. This is due to the resistance and inductance of the electrolytic output capacitor. Sometimes a 1 to 10 uF or larger tantalum or ceramic capacitor will help more than increasing the size of the output electrolytic.

9. Be sure to bypass the input to the regulator with a 100 µF capacitor.