ECSE 371 Lab #11

Closed-Loop PWM Motor Speed Control

Review the Bob Pease article on PID Control, as well as the other items on Canvas. Also, HH, 13.2.8 and 13.2.9.

Please read the entire lab before you begin!! See Step 6 for the Saturday Schematic

STEP 1, PWM generator:

Design, build, and test a circuit that produces a ~15KHz rectangular waveform (viewed on oscilloscope) with a duty-cycle that can be smoothly and (approximately) linearly varied from near zero to near 100% as an input control voltage of is varied; this will be similar to the design you did for the switching power supply. The triangle or sawtooth waveform that you are using should have a magnitude of about 10Vpk to provide adequate noise immunity. Use a reference Zener diode, a potentiometer, and a voltage divider to provide the 0 to 10 V control voltage. Operate the PWM circuit on 15V to 18V, single supply.

Caution: *for the remainder of this lab, you must configure the bench supply for parallel operation, because the motor will draw up to 10 A under full load. Note that test leads must be used to externally wire the output terminals in parallel. You must consult the power supply instructions at:*
http://engineering.case.edu/lab/circuitslab/sites/engineering.case.edu.lab.circuitslab/files/docs/HeTest_3005F-3_Power_Supply_Operation_090407.pdf

STEP 2, MOSFET stage and initial open-loop motor tests:

Add a MOSFET output power stage to the rectangular-wave output of your PWM circuit; you may use an N-channel or a P-channel. The PWM generator and the MOSFET power stage will be powered by the 15 to 18V bench supply, configured as discussed above to provide 10 A; the output of the circuit is to be used to provide a unipolar PWM voltage to the large permanent-magnet DC motor. Remember to include a 1N5819 (or equivalent) Shottky diode* across the motor to suppress the motor's inductive kick.

The power stage will handle very high currents and must be assembled on a soldered perforated board. See comments below.

You can load the motor (requiring it to produce more torque) by resistively loading the output of the coupled generator with a power rheostat; the generator and load resistor comprise a *dynamometer*. Full load "FL" for this lab is when the generator load is set so that the average *motor* current (**not** the generator current) is about 6 A.

Verify that you can **smoothly** control the speed of the motor by manually adjusting the duty-cycle of your circuit with the 0-10V control voltage; this is ***open-loop*** control.

STEP 2(a):

Use a current probe to view the motor and diode currents. (Carefully review the instructions when using the current probes; **only use it on insulated wires**. Always verify calibration of the current probe and scope - check this with a simple DC measurement).

If your circuit does not work perfectly in open loop, it will never work when you close the loop later in the lab. There should be no oscillation, discontinuities, or switching glitches; check carefully for smooth, linear control of motor speed, and check the current and voltage waveforms on the oscilloscope.

► At a motor current of about 4 A, and a supply voltage of 15V, record the voltage and current waveforms of the motor and diode. ***Be prepared to discuss these waveforms.***

STEP 2(b):

Obtain R_{DSon} from the data sheet for the MOSFET you are using. Assuming maximum duty cycle (near 100%), estimate the MOSFET power dissipation including resistive and switching losses. You will probably have to include some sort of simple heat sink and avoid long-duration tests at heavy load.

► **$P_{d(max)}$ of MOSFET_____ W**

STEP 2(c):

Is the current rating of the 1N5819 adequate? You may use the "math" measurement feature of the scope to determine power dissipation, or you may simply estimate. Be prepared to explain your answer. Must you always use a fast recovery part?

► **P_d of 1N5819_______ W**

STEP 3, Add incremental encoder:

Equip your motor with an incremental encoder to monitor RPM: Arrange an IR emitter/detector pair to sense the pattern on the edge of the 60-tooth reflective encoder disk; discrete IR emitters and detectors are available in the parts drawers. Use a small piece of perforated copper-clad board and necessary hardware to mount the emitter and detector such that the pair provides a usable speed signal. Remember: (a) *the angle of incidence equals the angle of reflectance"*. (b) The focal length of the emitter and detector is about 0.1".

Provide a circuit that will square up the detector output and provide a clean logic signal with a frequency and that is proportional to RPM. Some signal conditioning may be necessary in addition to a comparator. Vary the motor speed and confirm that the sensor circuitry is working properly. At 15 VDC, the no-load motor speed will be around 5000-7000 rpm. Note that by measuring the frequency of the sensor output you can determine the motor speed; you may use the "frequency counter" function of the oscilloscope.

STEP 4, Open- loop speed regulation tests:
STEP 4(a):
Record the approximate minimum RPM at which he motor runs smoothly without "cogging" (@ NL):
►**Minimum speed:**___150___**RPM**

STEP 4(b):
a) Measure the open-loop **load** regulation of the motor when running on your PWM circuit (as in Step 2 above): first, operate on a 15V supply and adjust the PWM duty cycle for a NL speed of about 75% of maximum; record the NL speed. Then, run the motor at FL by loading the output of the *generator* with a rheostat: Set the rheostat resistance so that the *motor* current (not the generator current) is about 6A; record the FL speed. Calculate and record load regulation. (NL to FL, where FL is when the average motor current is about 6A.)
► **NL speed:** ___4000___**RPM** ► **FL speed:** ___1000___**RPM**
► **Open- Loop load regulation:** ___75___**%**______________

STEP 4(c):
Measure the open-loop **line** regulation of the motor at no load. As before, operate at 15V and adjust the PWM duty cycle for a NL speed of 75% of maximum. Record the NL speed. Next, increase the power supply voltage to 18V and again record the NL speed.
► **Low- Line speed:** ___4000___**RPM** ► **High- Line speed:** ___4600___**RPM**_
► **Open- Loop line regulation:** ___15___**%**______________ _________

STEP 5, F to V converter:
Design, build, and test a frequency-to-voltage converter that will provide a DC voltage proportional to RPM when driven by the output signal of your encoder. Your F-to-V converter must be active over the full expected speed range of the motor. Assume that the minimum motor speed will be about 20 RPM.

STEP 6, Close the loop and perform initial tests:
Modify your circuit to incorporate *proportional* (P) closed-***loop*** **feedback** to regulate the speed of your motor from around 20 rpm to near-maximum (MOSFET on continuously). The speed of the motor (the "setpoint") will now be set by a reference voltage provided by a potentiometer (you may use the one that was previously used to set the control voltage). An error amplifier will compare the reference voltage (setpoint) to the RPM signal provided by your F-V converter; the error amplifier will adjust the PWM duty- cycle until the speed error is zero. Be sure to utilize the potentiometer over its full rotation so that good setpoint resolution results. You may try adding *integral* (I) control to improve performance.

Adjust the error amplifier gain and other variables to optimize speed regulation as well as response time to a step change in setpoint or output torque. You can produce such a step change in torque simply by connecting and disconnecting the generator load resistor. The lower the minimum RPM, the better your circuit is working.

Be careful with the response time of your F-V converter. Your goal should be a motor control that responds quickly to changes in load or setpoint without oscillation or excessive overshoot. Keep the response time of your F-V converter as short as seems reasonable.
If there is too much ripple in the output of the converter, the motor speed may exhibit noticeable ripple; on the other hand, if the cutoff frequency of the filter is too low, the controller may be unstable or response time to torque changes may be too slow.

Note the following:
1. The 0-10V control voltage was used in step 2 to change the speed of the motor; this was done to demonstrate open-loop PWM. After the circuit is converted to closed-loop operation, speed will be adjusted by changing the setpoint potentiometer, and the error amplifier will change the PWM duty-cycle.

2. Later in this lab the power supply will be varied from 15 to 18V. Your F-V converter and/or other parts of your circuit must properly function over this range. However, since you are now operating **closed loop**, it should not matter if the PWM duty cycle changes as the supply voltage is varied -the error amplifier should do its job and override these changes

►Saturday: Email a preliminary schematic of your complete closed-loop circuit.◄

STEP 7: Performance testing.
STEP 7(a):
Record the approximate minimum RPM at which he motor runs smoothly without "cogging" (@ NL):
►**Minimum speed:**__100__ **RPM**

STEP 7(b):
Verify that your circuit has enough proportional control: Confirm this by running at minimum speed and stalling the motor (or trying to); the motor voltage must increase substantially.
► **NL Motor voltage at minimum speed: _______V**
► **Motor voltage at minimum speed -setting under stall condition: _______V**

STEP 7(c):
Line regulation: Measure the change in RPM (at nominal FL and 75% of max speed) as the supply voltage is varied from 15V to 18V. Calculate and record line regulation.
► **Low Line speed: ___________RPM** ►**High Line speed: ___________RPM_**
► **Closed- Loop line regulation: ________%**

STEP 7(d):
Load regulation: Measure the change in RPM (at ~75% of max speed and Vsupply = 15V) as the load is varied from NL to FL. Calculate and record line regulation.

► **NL speed: ______________RPM** ► **FL speed: ______________ RPM**

► **Closed- Loop load regulation: _______%**

STEP 7(e):

Load Step Response: Run the motor at FL, then generate a step to NL by quickly disconnecting the rheostat from the generator. Measure the approximate time it takes for the motor to reach steady-state after the step change in load.

►**Approximate step response_______________ Sec**

STEP 8,

For optimum performance, you need a speed signal that has low ripple at very low speeds (20 rpm or less, for example); therefore, your F-V converter needs an averaging filter with a long time constant. Unfortunately, with a long delay in the F-V converter, it might be difficult to stabilize the system and response time will be poor.

The solution is to use an F-V converter that will quickly respond to a speed change, yet still provide low ripple. You could accomplish this with an encoder disc that provides more pulses; this would permit the use of a LP filter that has a higher cut-off frequency, and faster response would result. Or, you could keep the number of pulses/rev the same and you could find a way to provide a LP filter with a shorter delay. Think about using a S&H here.

Redesign your F-V converter for faster response. Then adjust your feedback values and see if the performance of your system improves.

►**Record your observations.**

For recitation, keep the circuit in Step 8 set- up and operating.

Comments:

1. GRADING: The lab will be graded according to the performance of the circuit. Performance will be determined by speed regulation, and by the ability of your circuit to quickly respond to step changes in the setpoint or in the load. The motor should rapidly and cleanly move to the new operating point, without overshoot ("underdamped") or undershoot ("overdamped"). Also, your control should work down to very low speeds (<20 RPM if possible).

2. ASSEMBLY:

This is a **high-power, fast switching-speed** circuit. Do not try to build the MOSFET section on the plug-in breadboard. Instead, Mount the MOSFET, Schottky, and gate driver on a small piece of perforated board using a compact layout with short, heavy wires. Leave a short loop of insulated wire to sense diode current using the current probe. Be careful how and where you connect the power section to the rest of the circuit, motor, and power supply. Bypass the power supply at your circuit, and at other critical places such as the error amplifier circuit and any reference voltages.

High rates of dV/dT and dI/dT can cause problems due to inductive voltage drops and induced voltages and currents. These problems can be minimized by keeping wire lengths short and current loops small. However, is best to optimize switching times: keeping them slow enough to minimize problems yet fast enough to reduce dissipation. Control of switching times is very easy with MOFETS. Because of gate capacitance, simply raising the value of the series resistance at the gate of the MOSFET will reduce switching times.

3. BEFORE USING THE SUPPLY IN PARALLEL MODE, USE BANANA LEADS TO PLACE THE POWER SUPPLY OUTPUTS IN PARALLEL!!! Failure to do this may damage the supply. Please read the instructions.

4. To load the generator (dynamometer), use one of the large rheostats that are in the lab. DO NOT EXCEED THE CURRENT RATING NOTED ON THE RHEOSTAT. The maximum generator output current will be around 8 amps.

5. In your lab report, include a complete schematic as well as the values of the parameters measured in the various steps. Also, your observations where asked.

6. It may be helpful if, when first closing the loop, you temporarily operate your PWM circuit from a separate (HP) bench supply, and the MOSFET/motor section with another, separate supply. Isolating the power supplies may make things easier because the high motor currents will not affect the PWM generator. Naturally you will have to provide a "common" ground connection for the two supplies.

In this way you can, for example, change the motor supply only and see if the motor speed changes – without worrying about what your control circuit is doing. This can be a quick and valuable test.
Remember to not exceed the power supply current limit – even under pulse conditions!!. If the bench supply goes into current limit it will drive you and your circuit crazy as the power supply output voltage changes.

7. You will have a problem when operating at very low RPM. At low RPM, the F-V output will have very high ripple. This ripple will be amplified by the error amp, and speed variations will be seen at the motor. We have also found that these bench supplies (and many supplies) may have trouble with the varying peak currents; the current limit may cut in early and screw up your circuit. Therefore, I suggest you be sure to get the project completed before you spend too much time trying to get good, steady performance below 100 RPM or so.

If you stay at higher RPM you should have no problem stabilizing the circuit – as long as you do not have noise problems, comparator glitches, etc. and your error amp gain is not too high. Also remember to keep your MOSFET rise and fall times relatively slow so as to not fill the air with unnecessary EMI.

8. When the motor is running NL, you are still drawing 1-2 A. This is 10 – 20W or more, so you will feel the motors get warm. At high torque you are talking 100W or more, and this is a lot of energy. Be careful with your MOSFET temperature.

9. Regarding the "fast" F-V converter to be used in Step 8: Start thinking about it this way:

Draw a nice diagram of the output waveform of the LP filter and the encoder pulse train. Do this for a few different RC time-constants and frequencies.

Note that if the time constant is small and the frequency low, you will have a lot of ripple. However, see if you can find a way to use a sample-and hold so that you end up with a fast-responding, constant voltage that is closely proportional to the average value of the pulse train.

(You may simulate this, of course).

*We have fast-recovery and Schottky diodes in the lab. However, if you are ever in an emergency

A note on driving loads with PWM waveforms: a mechanical device, such as a motor, will respond to the average value of the PWM waveform. For example, with a 50% duty cycle motor will operate at half the speed that it would if the duty cycle were 100%.

However, a resistive device, such as an incandescent lamp or resistance heater, will respond to the RMS value of the waveform. This is equal to the waveform peak voltage times the square root of the duty cycle. For example, a lamp operating on a 10Vpk, 50% duty cycle PWM waveform will see the equivalent 7.07V instead of 5V: