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1. MOSFET Proper Handling Procedure

A WARNING ABOUT MOSFETS AND STATIC ELECTRICITY

Until it is properly mounted with a gate pull-down resistor, a MOSFET is very sensitive to burn out if its gate terminal is touched. **Do not take the MOSFET out of its anti-static bag until you are ready to mount it on the PC board, and then always use a grounded static wrist strap and/or static mat when handling the MOSFET.** Avoid touching the gate terminal. (*Reference MOSFET pin out on the last page of this document.*)

When using a wrist strap, attach the wrist alligator clip end of the strap to the metal switch plate cover on the right-hand side of the lab benches. As an extra precaution, frequently touch the metal power switch plate cover with your hand. This removes charge from your body that could otherwise damage the MOSFET.

Pass/Fail Testing a MOSFET

If you suspect that your MOSFET has failed, perform the following pass/fail test. Note, this test would not be sufficient in a production environment to ensure the MOSFET would deliver years of fail-free service.

1. Remove any connections to either the drain or source terminals, except keep the 100 k Ω pull-down resistor connected from gate to source.
2. With no V_{GS} applied, measure R_{DS} with an ohmmeter. Expect $R_{DS} \rightarrow \infty$ (i.e., M Ω s).
3. Now, while measuring R_{DS} , apply 6 to 15 V_{dc} to V_{GS} . Expect to see $R_{DS} \rightarrow 0$ (i.e., few tenths Ω). Remove the temporary connection, and expect $R_{DS} \rightarrow \infty$.

Aside: This test can be also be performed with the MOSFET tester in the power lab. The tester circuit is mounted on a piece of wood and uses a 1" diameter red LED for testing under load.

2. Overview

MOSFETs are voltage-controlled switches (*whereas triacs are current-controlled switches*). Unlike triacs, MOSFETs provide controlled turn-on and controlled *turn-off* capability. They also switch much faster than triacs. However, a disadvantage of MOSFETs is that they are very static sensitive as the gate dielectric is generally just 100 \AA (*Angstrom = 0.1 nm*) thick, or less (***thus, please heed the Warning on page 1***). As illustrated in Figure 1, the MOSFET acts as a switch between the drain and source terminals, and has an internal antiparallel diode. An applied gate-to-source voltage of approximately 4 or 5 V_{dc} is sufficient to turn on the MOSFET (i.e., resistance between drain and source becomes a few tenths of an ohm). Faster turn on is achieved when 12-15 V_{dc} is applied. Then, when the gate-to-source voltage is again set to zero, the MOSFET turns off (i.e., drain-to-source resistance again becomes very large $\rightarrow M\Omega$ range).

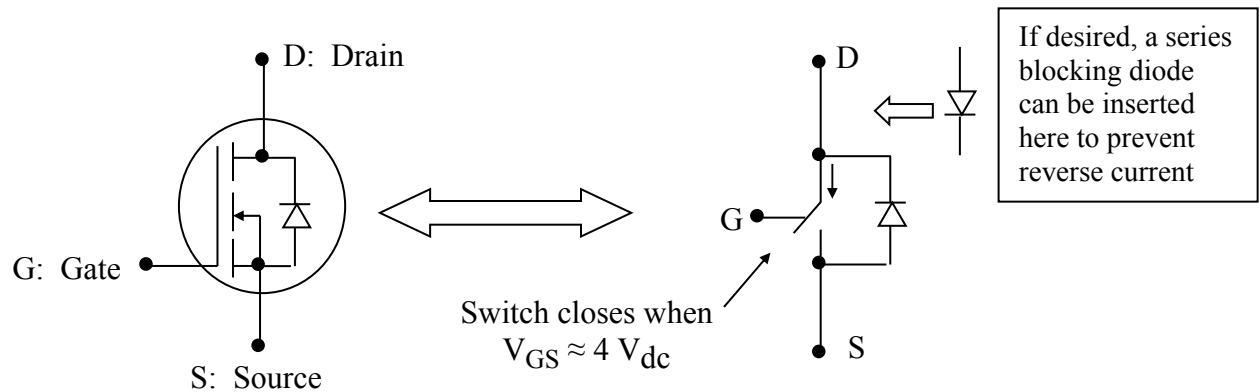


Figure 1. N Channel MOSFET Equivalent Circuit

3. The Firing Circuit

The MOSFET firing circuit used in this experiment, shown in Figure 2, contains five integrated circuit (IC) chips (i.e., a pulse-width modulator (PWM); an op-amp; a MOSFET inverting driver; a $\pm 12\text{ V}_{\text{DC}}$, dual-output, dc-dc converter; and the n-channel MOSFET itself which will act as your control switch). Pin outs for all five IC chips are provided at the end of this document.

The pulse-width modulator compares an internally-generated sawtooth wave to an externally provided $0\text{--}3.5\text{ V}_{\text{DC}}$ analog control voltage to produce a 5 V rectangular-wave logic output with controllable duty cycle D . As the reference voltage increases, D decreases (thus, an inverted response). This output serves as the input to the *inverting* MOSFET driver that, in turn, provides the voltage and current to quickly switch the MOSFET.

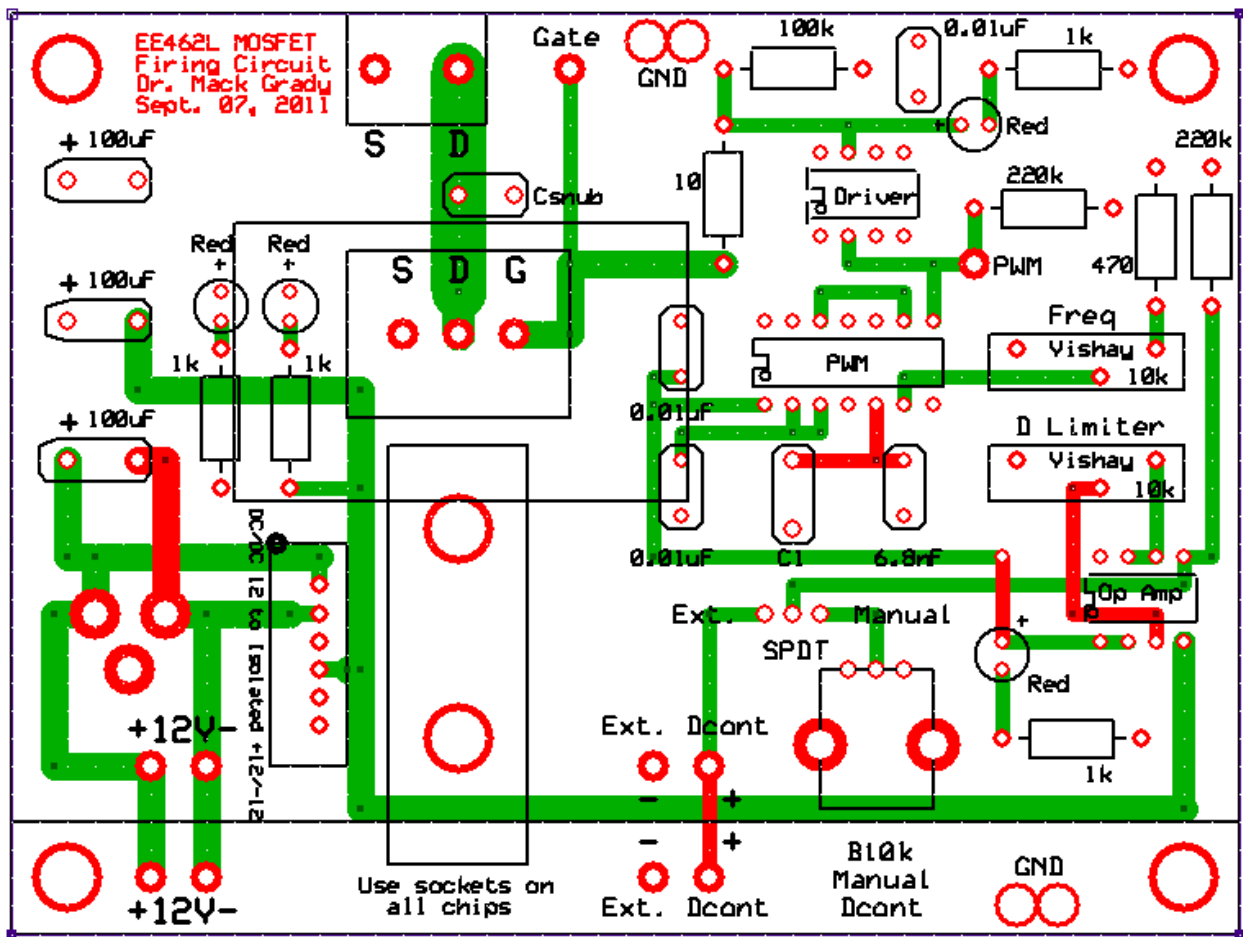


Figure 2. MOSFET Firing Circuit (ordered through ExpressPCB.com)

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Since the MOSFET firing circuit will be used for the three upcoming dc-dc converter labs as well, the duty cycle generation circuitry has been designed to accommodate the unique requirements of each of the converters. For example, the voltage divider for duty cycle control consists of two resistors and either an A10 k Ω potentiometer (for the Buck converter) or B10 k Ω potentiometer (for the Boost or SEPIC converters). The “A” in “A10 k Ω ” stands for audio taper, meaning that the resistance of the potentiometer varies logarithmically. B10 k Ω has a linear taper. In Figure 2, as the duty cycle “D” potentiometer (B10k Manual Dcont) is turned clockwise, voltage to the pin 1 of the PWM chip increases, the duty cycle of the pulses to the *inverting* driver chip decreases, so that D of the inverting driver output increases. The combination of resistors and potentiometer prevent D from exceeding 0.95 for the Buck converter, and 0.80 and 0.70 for the Boost and SEPIC converters respectively, so that the MOSFET is never fully “on” (an important safety feature for the Boost or SEPIC converters). There is also a 10 k Ω “D Limiter” potentiometer on the PCB board which can be adjusted to provide an upper control limit (UCL) for Dcont, to further ensure it won’t exceed certain thresholds which may be dangerous for the Boost and SEPIC converter operations.

The modeled variations for V_{out}/V_{in} vs. Potentiometer Angles are given in Figures 3a, 3b, and 3c for the three types of dc-dc converters to be studied in this course.

The sawtooth wave frequency of the pulse-width modulator is proportional to $1/(RC)$, where R is the series combination of an A10 k Ω potentiometer and 470 Ω resistor, and C is 6.8 nF. Decreasing R increases frequency. In Figure 2, turning the A10 k Ω “Freq” potentiometer clockwise decreases R, and thus increases frequency. As the potentiometer is turned clockwise, the amount of resistance change per angular degree of movement decreases. The nonlinear resistance variation of an audio pot yields a more linear variation of frequency than can be achieved with a linear potentiometer (see Figure 4).

D vs. Potentiometer Angle

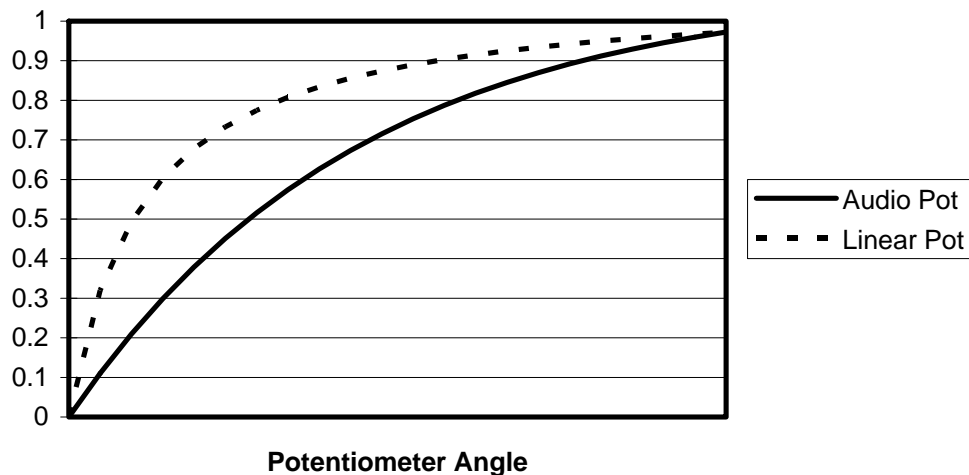


Figure 3a. Duty Cycle D (and V_{out}/V_{in}) Variation in Buck Converter vs. Potentiometer Angle (EE462L_MOSFET_Firing_Circuit_Duty_Variation.xls)

Boost Vout/Vin vs. Potentiometer Angle

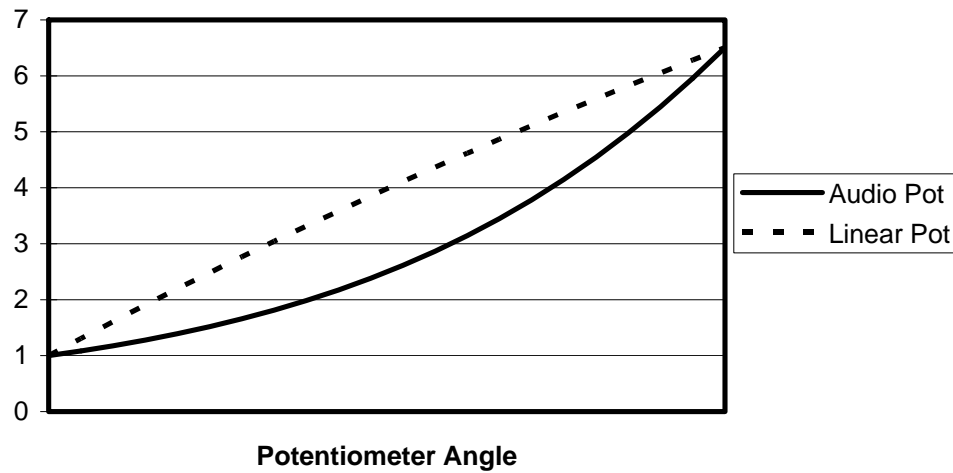


Figure 3b. Vout/Vin Variation in Boost Converter vs. Potentiometer Angle
(EE462L_MOSFET_Firing_Circuit_Duty_Variation.xls)

SEPIC Vout/Vin vs. Potentiometer Angle

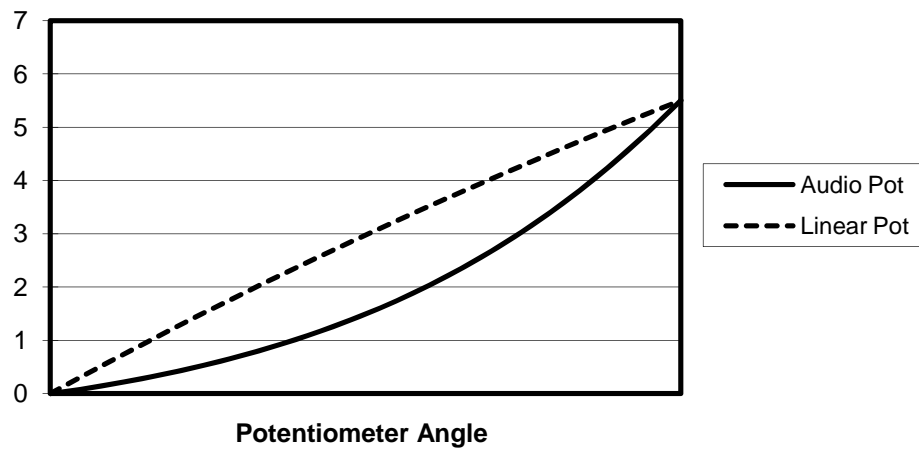


Figure 3c. Vout/Vin Variation in SEPIC Converter vs. Potentiometer Angle
(EE462L_MOSFET_Firing_Circuit_Duty_Variation.xls)

Frequency Variation vs. Potentiometer Angle

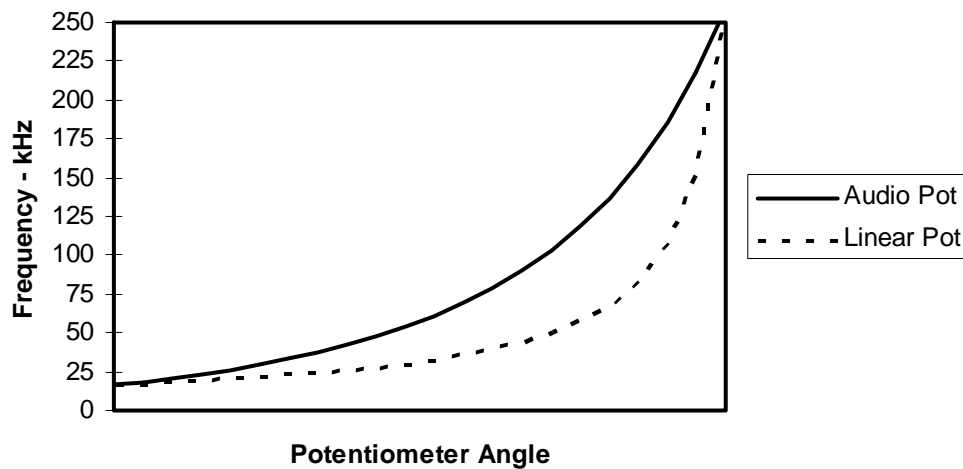


Figure 4. Frequency Variation vs. Potentiometer Angle
(EE462L_MOSFET_Firing_Circuit_Freq_Variation.xls)

4. Circuit Construction

- Ohm-check the PC board **before** mounting any components. This means ohm-checking each pad for connections to the ground plane, power plane, or neither plane. This is generally good practice before populating a PCB board to ensure there are no defects (shorts, opens, etc.) from the PCB manufacturer.
- For the for a 10 °C temperature rise with the trace thickness (not width) used on this board, 0.010” wide traces are rated at 1 A, 0.025” wide traces are rated 1.7 A, and the widest available trace of 0.150” is rated at approximately 5.9 A per mil standard 275. Traces can be paralleled, though it is more common to use thicker rather than wider traces to save board space.
- It is best to keep at least 0.2” between components
- Some people prefer not to have any traces on the bottom side.
- Use nylon screws and standoffs to support the PC board
- Wide traces are stronger, especially at corners, and easy to touch with a scope probe
- Some people prefer to use ½ W resistors because it is easy to attach a scope probe to their leads
- **Important:** Use sockets for the IC chips so they can be easily replaced (*if they burn out*), or removed for reuse.

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Next: Temporarily connect just the dc jack female socket to the end of a 12 V_{dc} regulated wall wart and plug the wall wart into a wall outlet. Use a voltmeter to determine which pin on the dc jack is +12 V, and which pin is ground. Now, disconnect the wall wart. Then,

1. Mount and solder the 100 k Ω MOSFET gate-to-source pull-down resistor.
2. Mount and solder the three-terminal Phoenix Contact “green plug,” so that the tightening screws face the outer edge of the PC board.
3. Mount the 1.5” steel corner bracket with two #6 nylon knurled-head thumb screws, using a 1/4” #6 nylon spacer between each screw and the surface of the PC board.
4. **The most important step: use a static wristband. Avoid touching the gate terminal.** Take the MOSFET out of the pink antistatic bag, place a very thin layer of heat sink compound on the back of the MOSFET (*if available, do not get it on your fingers or clothes as it is hard to remove*), and run a #4 nylon knurled-head thumb screw through the MOSFET and heat sink holes. Insert the MOSFET pins into the green plug and push the #4 thumb screw through the 1.5” bracket. Place a 1/8th inch, #6 nylon spacer on the back of the corner bracket, and tighten the assembly with a #4, 3/4 inch threaded spacer. Then, tighten the green plug’s three screws to make a solid electrical connection with the MOSFET’s pins.

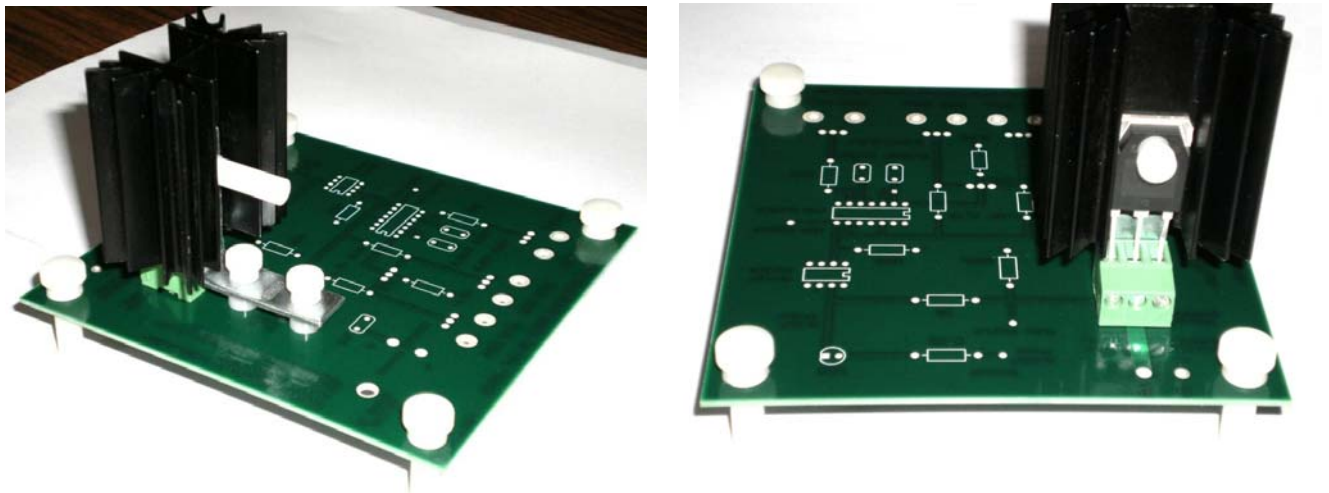


Figure 5. Example of MOSFET Assembly. Actual PCB configuration may differ from those shown in these pictures.

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5. Mount the dc jack. Before *soldering* any leads to the jack, plug in a 12 V_{dc} wall wart to determine the + and – terminals on the PC board. Then, disconnect the wall wart.
6. Mount all remaining components. General practice is to solder the smallest components and the ones with the most pins (i.e., IC chips) on first, since it's always easier to solder larger components later on. *(The converse of this statement doesn't always hold true!)* Again, make sure you use sockets for your IC chips so they may easily be removed or replaced if they burn out! You wouldn't want to have to repopulate a whole new PCB board from scratch! *Note: Should you need to remove an IC chip for some reason, use the chip pullers provided as part of your toolkit, and pull straight up (so pins don't bend).*
7. Plug in the wall wart. Make sure that each chip is receiving the proper +12 V supply voltage. This should be pins +V_{CC} for the Op Amp and PWM modulator, and V_{DD} for the inverting driver chip. Pin out diagrams contained at the end of this document may be helpful. Do this using multimeter measurements directly at the appropriate pins on the chips, or, the oscilloscope probe may be used if grounded to the PCB board. *(Feel free to clip your oscilloscope probe's ground to the two **adjacent** GND holes OO on the PCB board.)* Also, check the voltage at pin 12 of the PWM modulator chip (V_{ref}), with respect to ground. Expect 5 V_{dc}.
8. Unplug the 12 V_{dc} wall wart, and connect an oscilloscope probe to the logic output of the PWM chip (i.e., pin 8). Now power back up your PCB board and adjust D. *(Note: Adjust D via the "B10k Manual Dcont" potentiometer from Figure 2, not the D Limiter potentiometer!)* The waveform should vary sharply between zero and (about) 4.5 V, with an inverted duty cycle. Thus, read this waveform as "- Duty" (negative duty cycle) on the oscilloscope. *(Note: If the waveform is "chattering", adjust the Trigger level knob to something in between the signal range and it should stabilize.)*

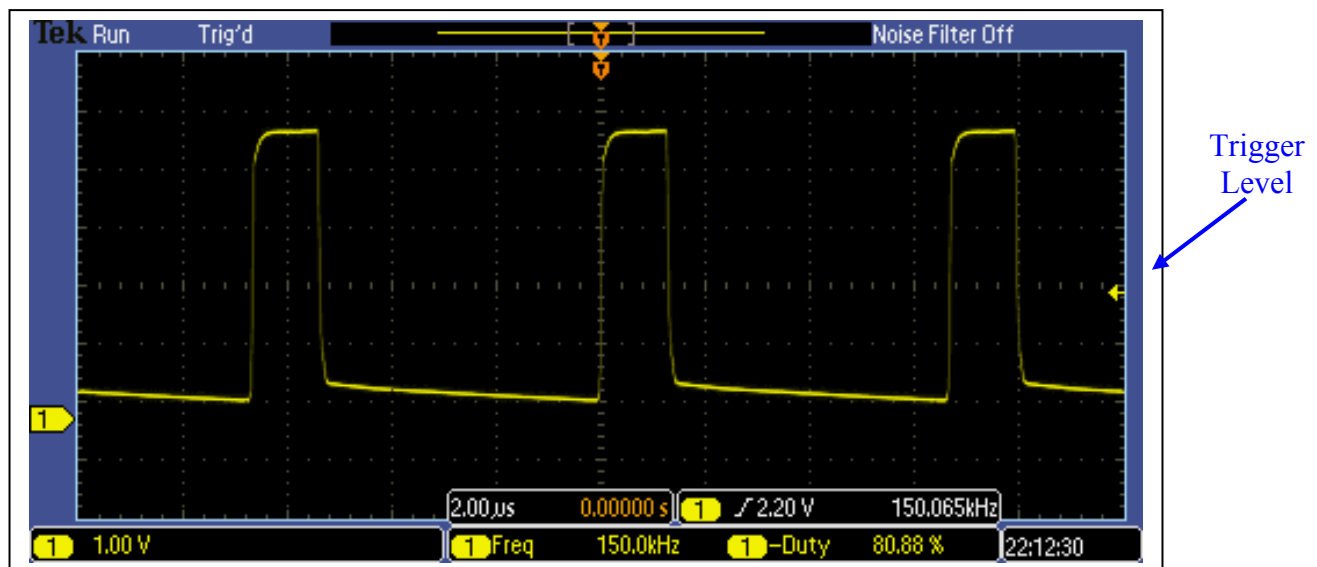


Figure 6: PWM Modulator chip,
Logic Output "E" (pin 8)

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9. Again depower your PCB board and move your oscilloscope probe to “Output A” of the driver to view V_{GS} . Re-energize your PCB board with the wall wart. The V_{GS} waveform you see is “open circuit” because the driver is not yet connected to the MOSFET. The waveform should be switching sharply between 0 and 12 V. Use the oscilloscope to measure duty cycle, D , and frequency, f . Vary the D and f potentiometers to observe the ranges of D and f . Expect $0.05 < D < 0.95$ (for Buck), and $15 \text{ kHz} < f < 200 \text{ kHz}$. D and f should increase as their respective potentiometers are rotated clockwise. (*Note: If D 's upper bound seems limited, adjust the “D Limiter” potentiometer and try again.*)

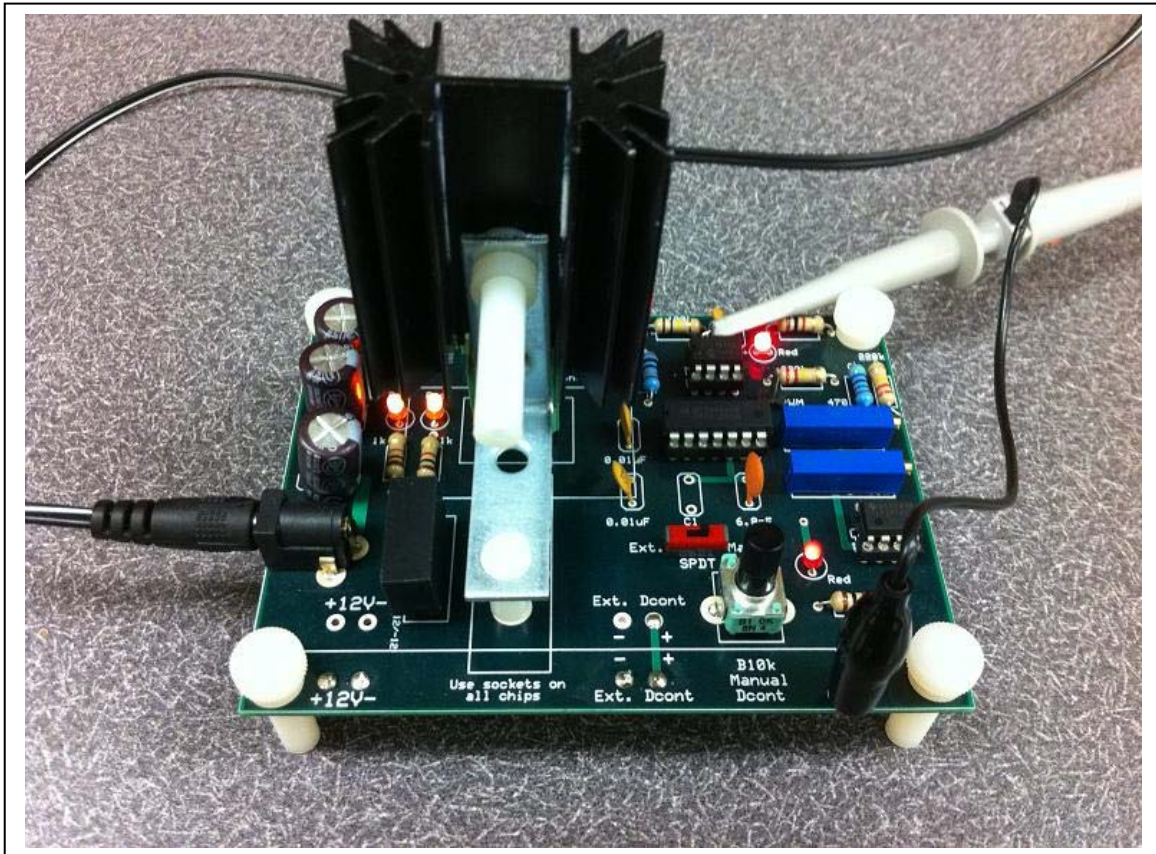


Figure 7: Reading pin 7 (Output A)
of the MOSFET inverting driver

10. Save a representative screen snapshot of V_{GS} for your report, with $D \approx 0.8$, and $f \approx 150 \text{ kHz}$. You should ensure your screen shot depicts the frequency and duty cycle, so you should make use of the “Add Measurement” function on the oscilloscope and add both of these. Just make sure you add “Positive Duty Cycle” (+ Duty) for V_{GS} . If the oscilloscope readings are jumping around, you may try adjusting the Horizontal scale to zoom out.

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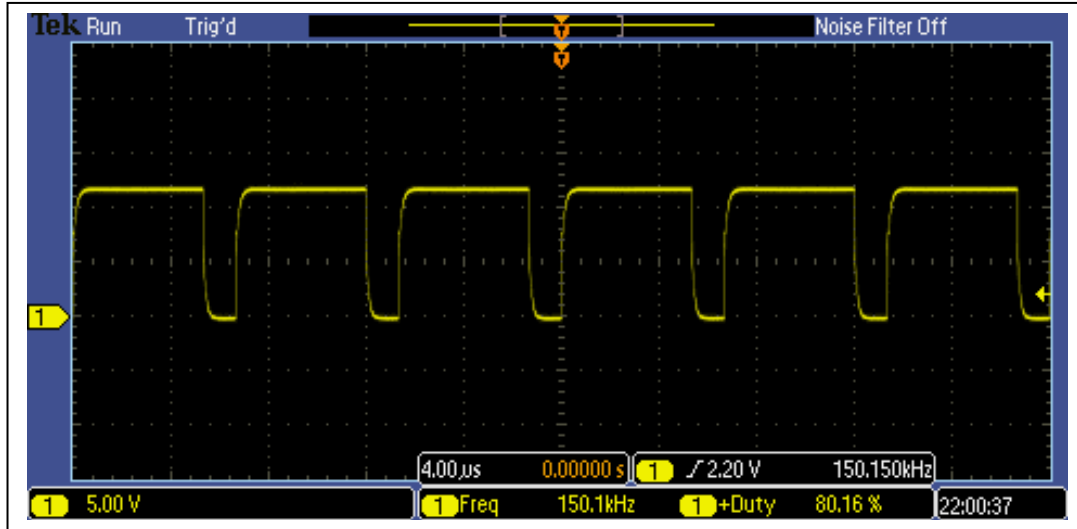


Figure 8: V_{GS} switching at 150 kHz
with a duty cycle \approx 80%

11. Now, still with no load connected to your MOSFET PCB board, adjust the frequency up to 200 kHz and, capture a screenshot similar to the one shown below (*showing the gate-source capacitance effect*). You may wish to reference the lecture notes, as well as increase the horizontal zoom more than what's shown in the figure below. Use this screen capture (**with appropriate cursor measurements**) to estimate your MOSFET gate-to-source capacitance and compare it to the dynamic capacitance characteristics from your MOSFET's data sheet: <http://www.fairchildsemi.com/ds/FD/FDA59N25.pdf> Comment on this effect, and these C values (measured vs. spec sheet) in your lab report.

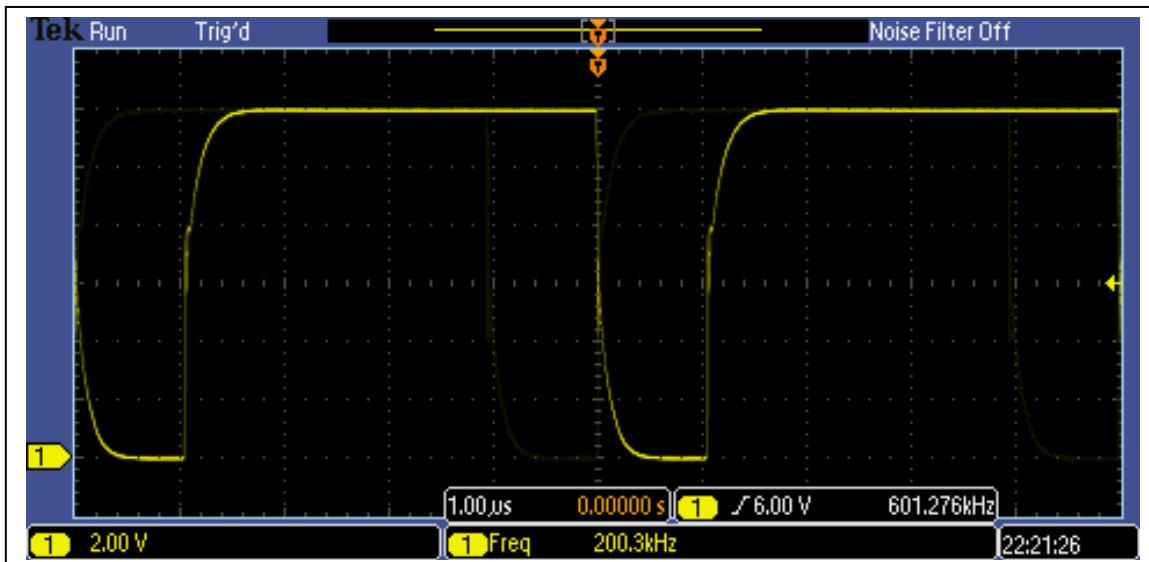


Figure 9: V_{GS} switching at 200 kHz,
 $D \approx$ 80%, showing MOSFET gate-source capacitance effect

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- Lower D to the minimum, and unplug the wall wart.
- Use #14 or #16 wire jumpers and connect your MOSFET firing circuit as depicted in the Figure below. Keep wires relatively short in length. Note that the $10\ \Omega$ power resistor and light bulb are in parallel, and the MOSFET is connected to the low-voltage side of the dc bus created by rectifying the output of the step-down isolation transformer. Also note the MOSFET is connected across Source and Drain. Lastly, the 150 W light bulb is not from your Light Dimmer circuit; it's just a standalone light bulb load found in the power lab.

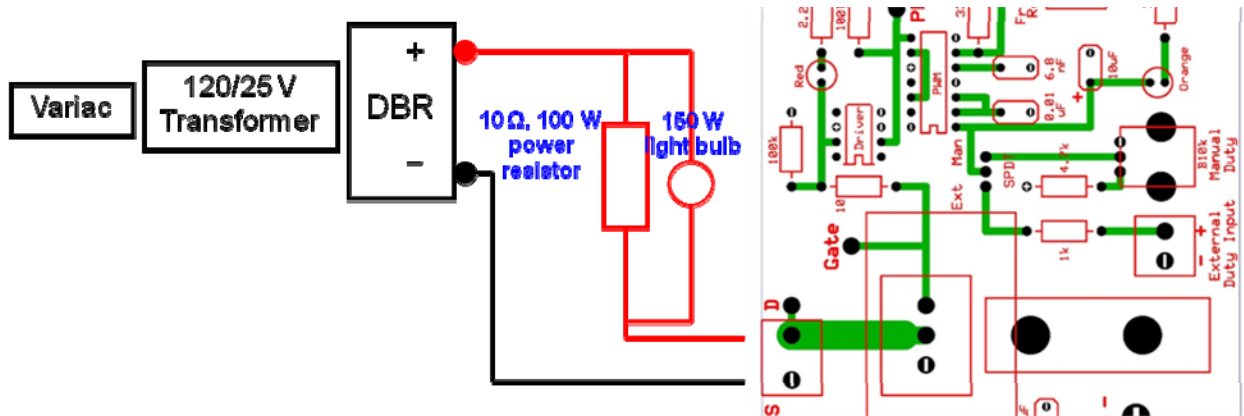


Figure 10: Using MOSFET firing circuit as a switch in a loaded dc bus

- Finally, screw a $0.022\ \mu\text{F}$ ceramic capacitor into / across the MOSFET drain and source green plug terminals. This will serve as a snubber capacitor and you will later test your MOSFET switching with and without (*hard switching*) this snubber to learn how it affects your MOSFET's switching characteristics.

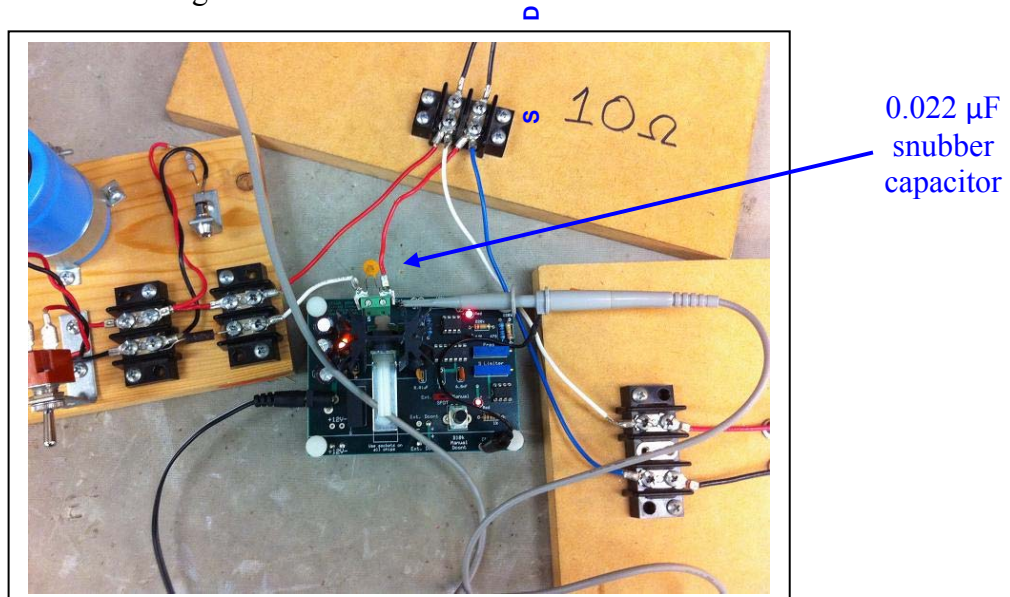


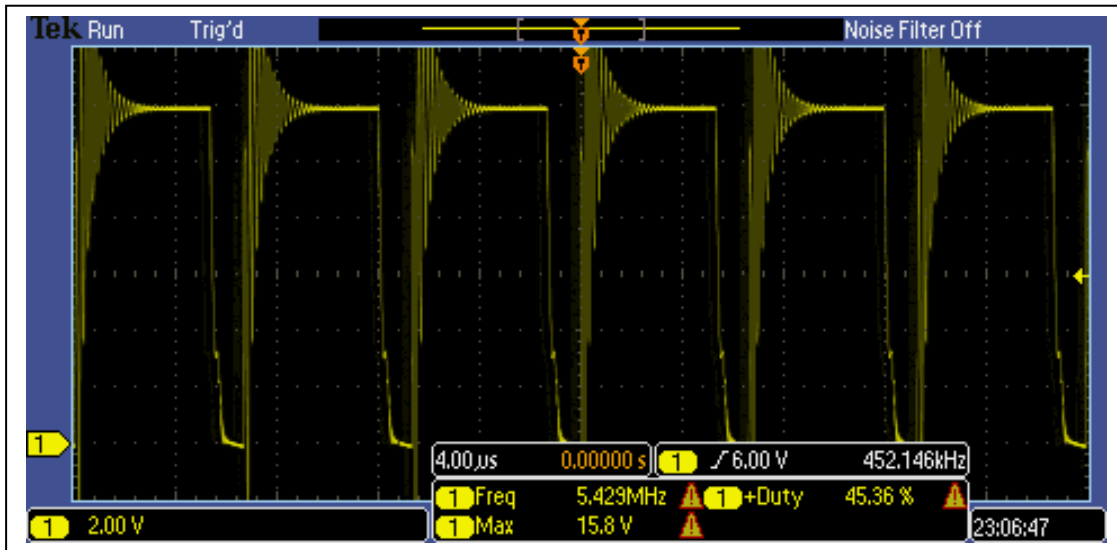
Figure 11: MOSFET and loads wired as in Figure 10, including the snubber capacitor across V_{DS}
(*Note: choice of wire jumper colors isn't optimal*)

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Figure 12: Full Set-up of MOSFET testing depicting Variac, 115:25 Iso Transformer, DBR, $10\ \Omega$ load & light bulb load in parallel, and MOSFET switch on low-voltage side of dc bus

15. Make sure the variac is OFF and set to 0 V. Plug in the $12\ V_{dc}$ wall wart to energize your MOSFET circuit. Now, turn “ON” the DBR switch, transformer switch, and variac switch, and slowly raise the variac output to 120 V.
16. Next, use the MOSFET as a dc light dimmer. Observe V_{GS} at the MOSFET on an oscilloscope while varying D and f over their ranges. Save the V_{GS} waveform with $D \approx 0.8$, and $f \approx 150\ \text{kHz}$. (Note: You will not be able to get accurate values for D and f with the “ringing” evident in your circuit due to capacitance and inductance effects. Thus, switch off your DBR to capture the correct D & f readings for V_{GS} , then turn it back on again to capture the O-scope waveform.)



Save screen
snapshot #3

Figure 13: V_{GS} waveform at $f = 150$ kHz,
 $D = 0.8$ for a loaded circuit condition

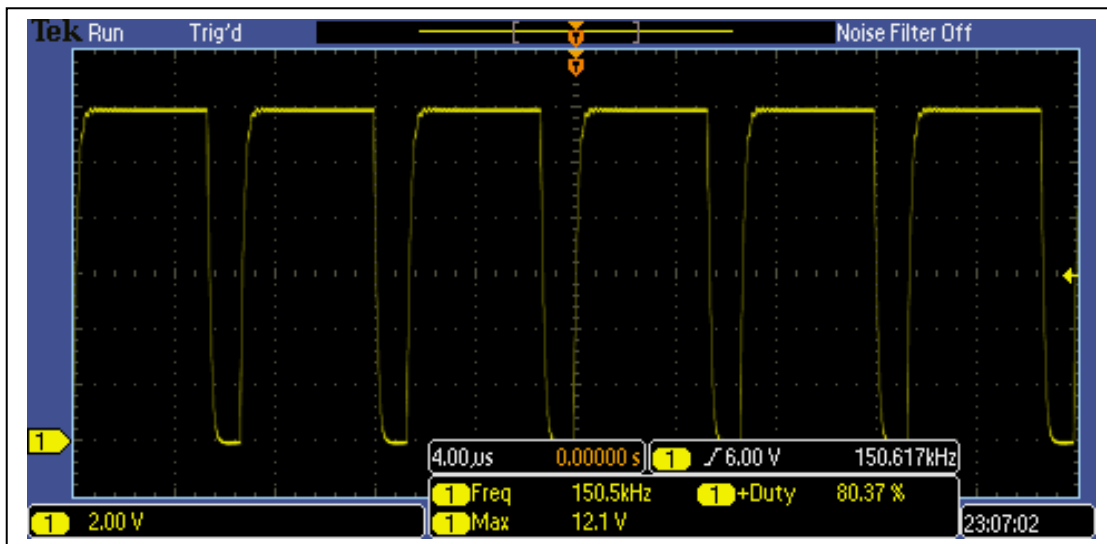


Figure 14: V_{GS} waveform at 150 kHz, $D = 0.8$
with DBR switched off (unloaded condition)
to view accurate values for f and D .

17. Now, move your probe to view V_{DS} at the MOSFET on an oscilloscope while varying D and f over their ranges. Save the V_{DS} waveform with $f \approx 150$ kHz, $D \approx 0.2$. Measure the peak value of V_{DS} , and use cursors to estimate both the turn-off and turn-on ringing frequencies. It may be helpful to remember that V_{DS} has an inverted duty cycle (- Duty). Explain why in your lab report!

As before, ringing will negatively affect your oscilloscope's ability to accurately capture the correct duty cycle reading. Try switching off the DBR as you did with V_{GS} . Did this help? Why or why not? If not, what other convention can you use to accurately measure the duty cycle? Please state what method you used in your lab report!

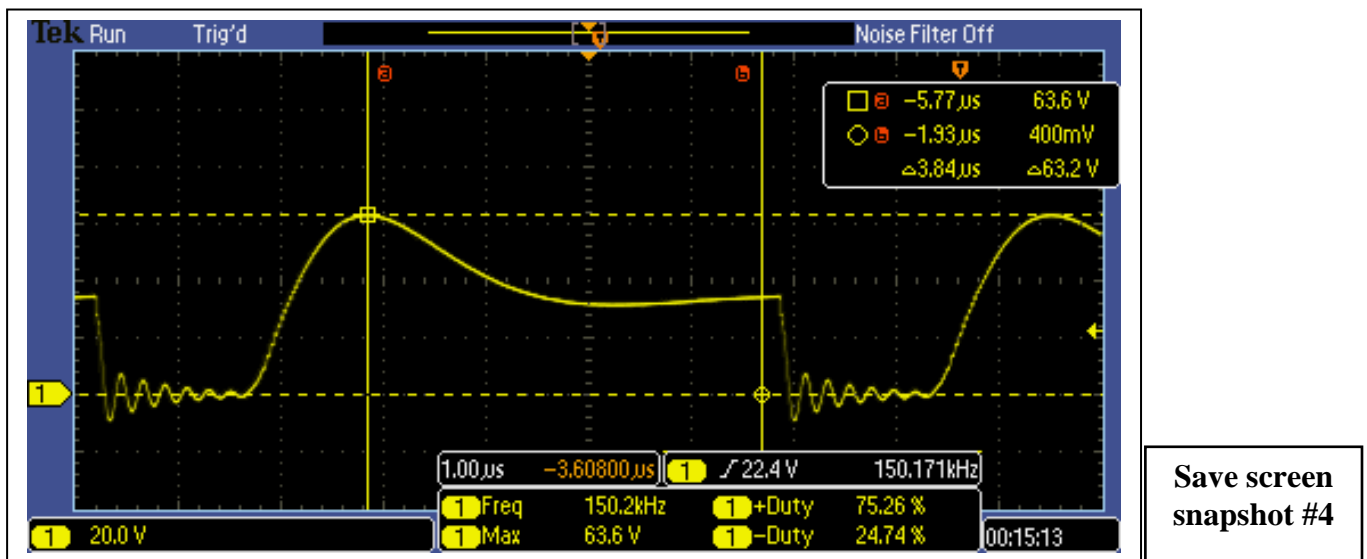


Figure 15: V_{DS} waveform at 150 kHz, $D = 0.2$, with snubbing capacitor, showing T_{OFF} ringing frequency, as well as V_{peak}

It's noted that your T_{OFF} ringing frequency will be somewhat subjective. Your 2nd cursor should be placed approximately where the waveform has recovered from 1st trough and has started to stabilize.

When reading your T_{ON} ringing frequency, it may be helpful to zoom in to get a more accurate reading / measurement of the turn-on period, T .

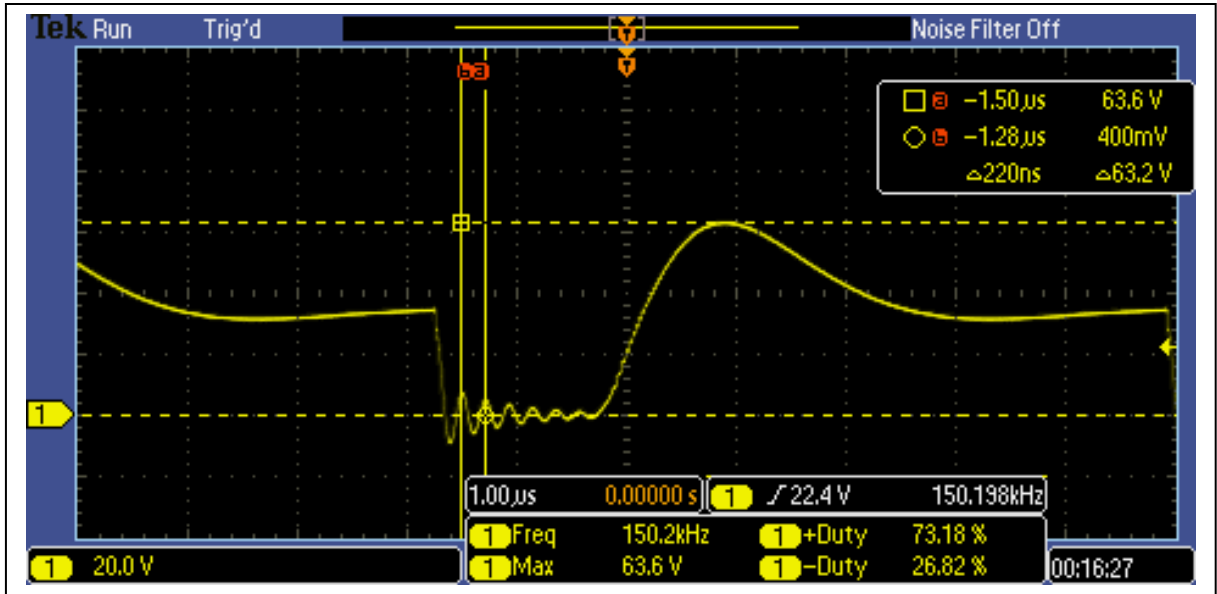


Figure 16: V_{DS} waveform at 150 kHz, $D = 0.2$, with snubbing capacitor, showing T_{ON} ringing frequency, as well as V_{peak}

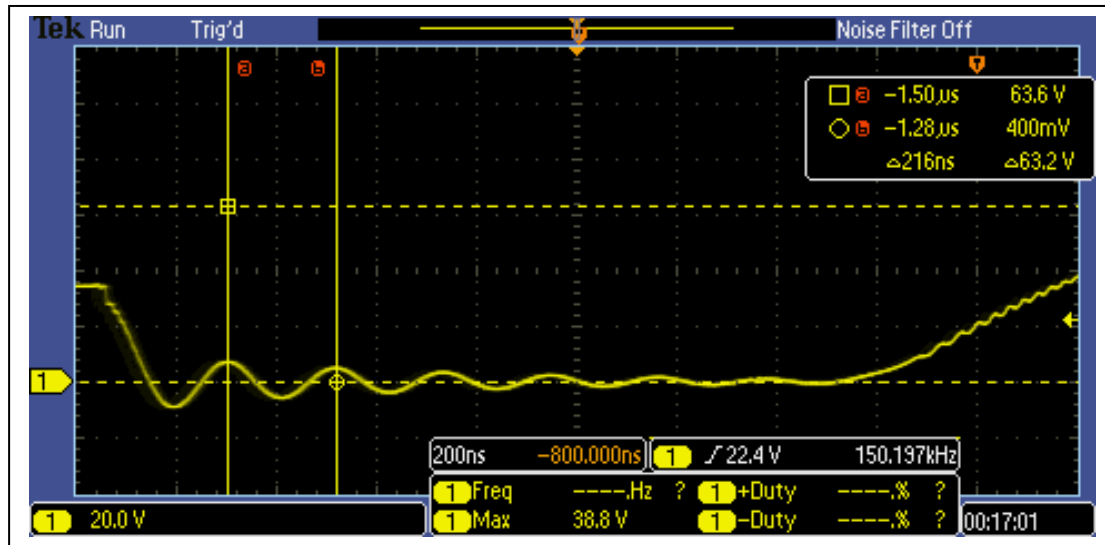


Figure 17: V_{DS} waveform at 150 kHz, $D = 0.2$, with snubbing capacitor, showing zoomed-in T_{ON} ringing frequency

18. **Turn off the DBR**, and then remove the snubber capacitor. Power up, and repeat the peak voltage and turn-off-and-turn-on transient frequency measurements. Observe the impact that the snubber capacitor has on the peak value of V_{DS} as well as the switching transients. **Note – do not remove or connect the snubber with DBR power applied because the resulting sparks can burn out the MOSFET.**

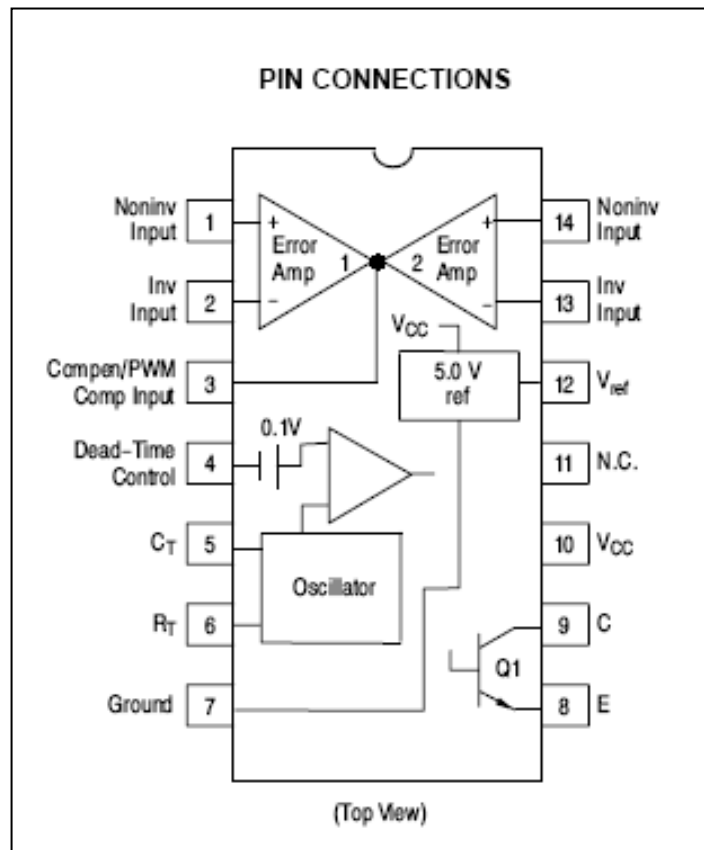
Based upon your experimental analysis, please record values for V_{peak} , turn-on, and turn-off ringing frequencies for a dc bus voltage of 20 V and 35 V, both with and without the snubbing capacitor placed across V_{DS} . (*Note: If a frequency cannot be accurately measured, please place “NA” in the table.*) You do not have to include all your oscilloscope figures since the methodology was already captured in the previous step’s required screen snapshots.

MOSFET V_{DS} switching transients			
$f = 150 \text{ kHz}, D = 0.2$			
<i>with</i> 0.022 μF snubbing capacitor			
V_{dc}	V_{peak}	T_{ON} frequency	T_{OFF} frequency
20 V			
35 V			
<i>without</i> 0.022 μF snubbing capacitor			
V_{dc}	V_{peak}	T_{ON} frequency	T_{OFF} frequency
20 V			
35 V			

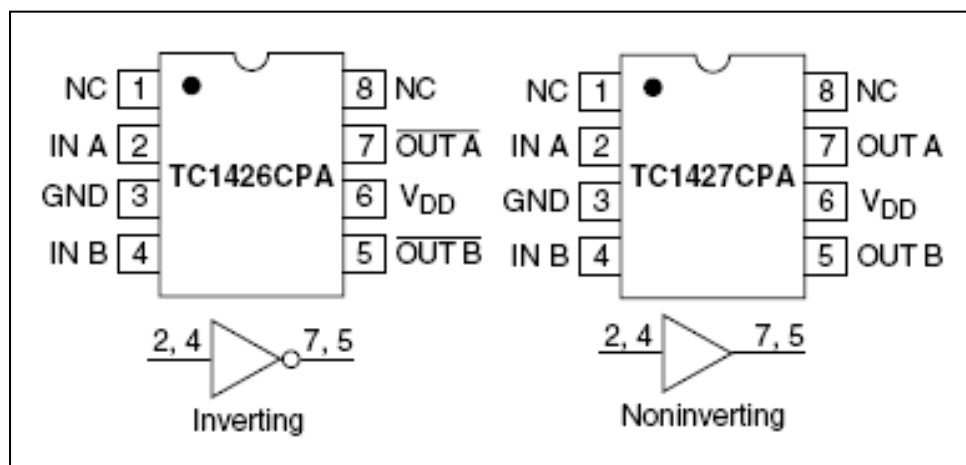
Comment on how the snubbing capacitor affects your peak voltage and switching transients and characteristics. If switching transients remain unchanged, explain why? Lastly, compare these peak voltages measured to the voltage rating of your MOSFET, located in its respective data sheet.

19. Optional: Repeat the previous step and construct another table at a frequency of 200 kHz.

5. Device Pinouts



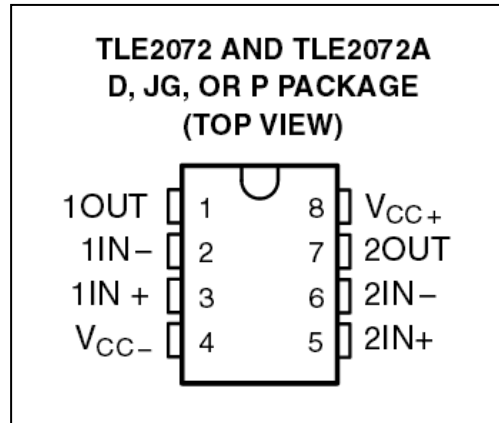
PWM Modulator (On Semiconductor MC34060A)



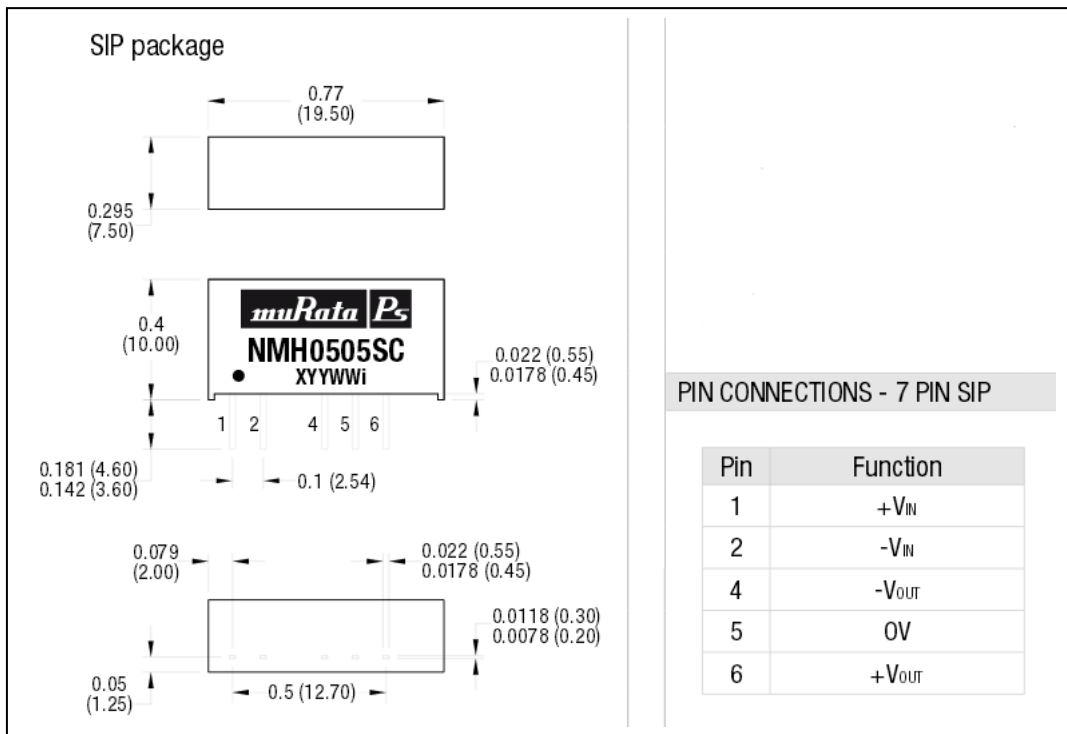
MOSFET Driver, Inverting and Non-Inverting, (MICROCHIP TC1426CPA and TC1427CPA, respectively)

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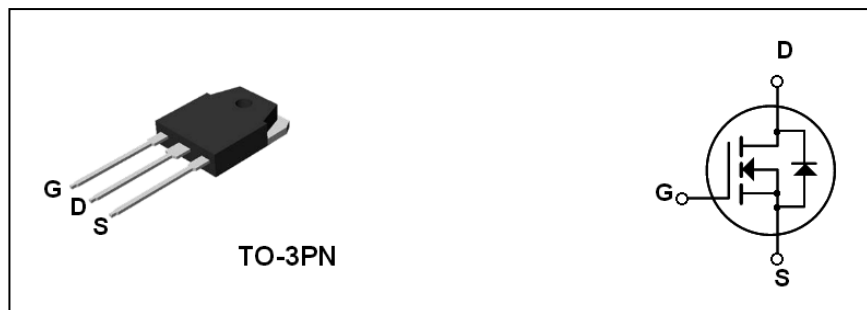
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TLE2072CP, Texas Instruments,
Dual Low Noise Op Amp



NMH1212SC, muRata Power Solutions, DC/DC Converter &
Regulator 2W, +12,-12V Dual Output



FDA59N25, Fairchild Semiconductor,
N-Channel UniFET™ MOSFET