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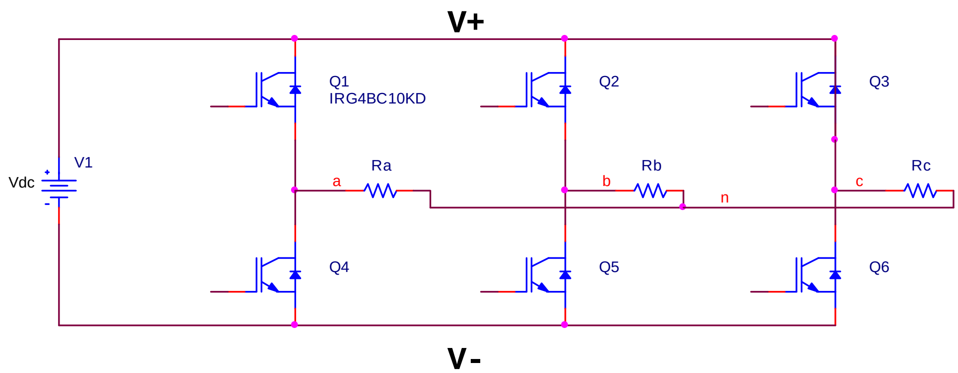
Lab 9: 3-phase Inverters and Snubbers

Pre Lab

<u>3-phase inverters:</u>

Three phase inverters can be realized in two ways: three single-phase inverters operating together, or one three-phase inverter. The three phase inverter is almost always the better choice. Following is a schematic for a three-phase inverter with a 3-phase, wye connected, resistive load attached:



Circuit 1 3-phase inverter

There's always one IGBT from each "column" on. Care must be taken to never have two vertically-aligned IGBTs on at the same time, because that would short the DC source.

Let's assume that a 3-phase, balanced ($R_a = R_b = R_c$), resistive load is connected to terminals a, b, and c of the inverter (as shown on the previous page). The load is connected in a wye configuration. Let's operate the inverter in the simplest way possible: 180^0 conduction. In this mode each IGBT is on for the same amount of time every cycle, and the IGBTs always operate in the same sequence. For this example that sequence is as follows:

135 >> 156 >> 126 >> 246 >> 234 >> 345 >> 135 >> etc

So for the first state, Q1, Q3, & Q5 are all on and all other IGBTs are off. For our purposes, when an IGBT is on it acts like a short. With that in mind, when Q 135 are on points a & c are shorted to V+, and point b is shorted to V-. This is the equivalent circuit:

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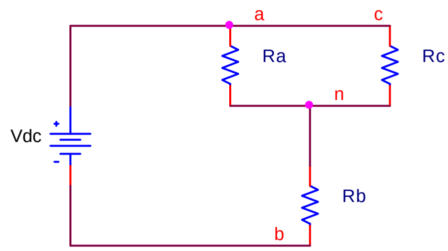

1. What is the line to neutral voltage across each phase of the load? i.e what's V_{an}, V_{bn}, and V_{cn}?

During the next state point a is shorted to V+, and points b & c are shorted to V-.

2. Draw the output voltage waveform for each of the phases as voltage vs. t (or wt if that's easier for you). Include at least one full cycle of each. Label the voltages on your plots in terms of V_{dc}. Show enough of your work (calculating the voltages) that your lab instructor can tell you didn't just look it up online.

3. What is the equation for rms line-to-neutral output voltage in terms of input DC voltage? This one you can look up; no need to derive it.

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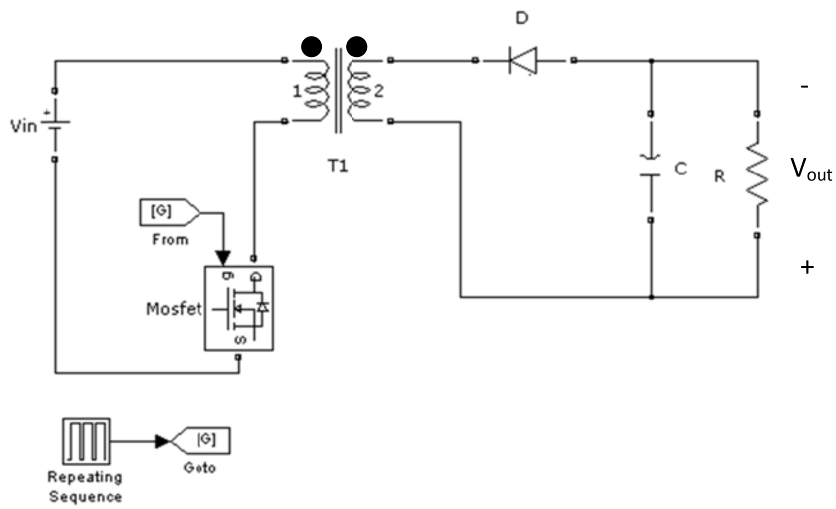
Snubbers

We've used lots of circuits in this class that have an inductor and a switch, and they've proven very useful to us. One aspect of these circuits that we've yet to look at is what happens the instant a switch is opened in an inductive circuit. Consider Circuit 2:



Circuit 2 Flyback converter

Circuit 2 is called a flyback converter. It's basically a buck-boost chopper whose inductor has been split in two to form a transformer. The equation for V_{out} with polarity shown is:

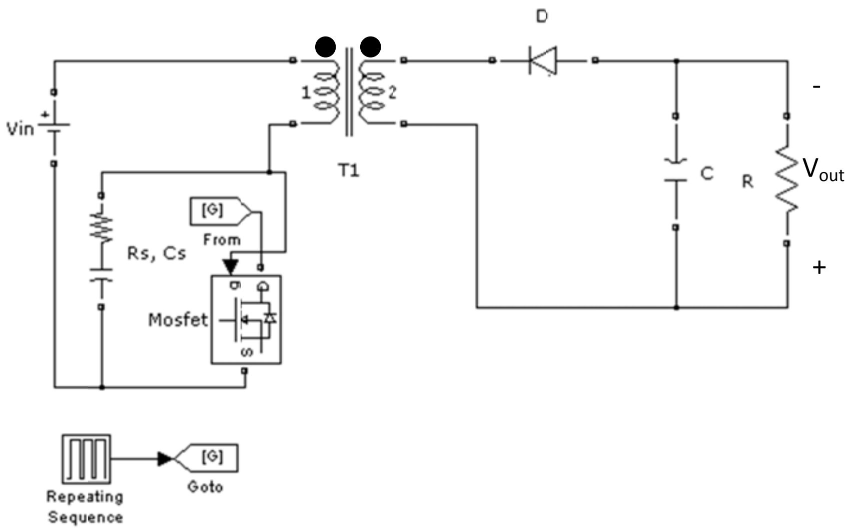
$$V_{out} = \frac{n_2}{n_1}\frac{D}{1-D}$$

n_2 and n_1 are the turns of side 2 and side 1 respectively. Flyback converters are used extensively in CRT monitors and TVs, cell phone chargers, printers, and many other applications. The main advantage they provide over traditional buck-boost converters is isolation between the input and output sides of the circuit.

Besides being extremely useful, flyback converters also do a good job of highlighting the need for snubbers. When the MOSFET is turned on, current flows through side one of the transformer, storing energy in the form of a magnetic field. If you've had energy conversion, you might have guessed that the effective inductance for this part of the operation is the core (magnetizing) inductance of the transformer.

1. When the MOSFET is opened, there's a danger presented to it. What is that danger and why does it occur?

The simplest solution to this problem is to use an RC snubber. An RC snubber is just a series RC network placed across the drain and source of the FET. Circuit 3 shows the flyback converter with the snubber in place.



Circuit 3 Flyback converter with RC snubber

The snubber gives the current a path to keep flowing even after the MOSFET is opened. The impedance of the snubber is much larger than the on resistance of the FET though, so it doesn't affect the operation of the converter. The optimal design of snubbers will be left to another day. For now we'll work with these general rule found in "Snubber Circuits: Theory, Application, and Design," by Phillip C. Todd of TI:

- C_s should be 2-4 times the output capacitance of the FET
- R_s should equal the characteristic impedance of the resonant circuit, which is $\sqrt{\frac{L_S}{C_S}}$. L_s is the leakage, or series, inductance of the transformer. Too many "s" subscripts…

2. If the output capacitance of a certain FET is 1500 pF, and the leakage inductance of a certain transformer is 30 mH, design a RC snubber for a flyback converter in which these components are used.

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Lab Exercises

<u>3-phase inverters</u>:

1. Hook up and run a 3-phase, 180^0modulation inverter. Connect a 200 Ω/phase, wye-connected load to the inverter. Use a 20 V DC source as input.
2. Take a screenshot of all three phases of output voltage on the scope.

3. What's the rms voltage of each phase? Is this L-L or L-N voltage? Does this agree with the predicted values?

4. Take a screenshot of the harmonic analyzer, looking at the voltage of one phase. What strikes you as interesting about the voltage spectrum?

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5. Now change the load to delta-connected and run the inverter.
6. Again, take a screenshot of all of the output voltages.

7. What's the rms voltage of each phase? Is this L-L or L-N voltage? Does this agree with the predicted values?

8. Are the spectrums of these voltages significantly different from the spectrums when the load was connected in wye?

If you'll remember way back to the previous lab, we saw that using pulse-width modulation (PWM) can have a huge positive effect on the harmonics. The switching is a lot more complicated for 3-phase inverters, so we'll let the LVDAC software take care of it for us.

9. Change to a 3-phase PWM inverter. Leave the load delta-connected.
10. Run the inverter so the "Peak Voltage" dial is at 50% of DC bus voltage. Take a screenshot of the harmonic analyzer and comment on it. Estimate the carrier frequency.

11. Using the harmonic analyzer, see what happens when you mess with the “Peak Voltage” control dial.
12. Now look at the gating signal for one of the IGBTs on the scope. Can you tell what type of PWM is being used?

Snubbers:

1. Build Circuit 2 (from pre-lab). Use 10V as your DC input. You choose the diode, output capacitor, and MOSFET. Use one of the transformers in or under the benches. Use a turns ratio of 1:1. Use the function generator to provide the gating signal. Use a 100 Hz, 50% duty cycle, square wave to gate the MOSFET.
2. Run the converter first without a snubber. Observe the output voltage as well as the drain-to-source voltage of the MOSFET. Use the scope on the bench, rather than the LVDAC-EMS scope to observe the waveforms.
3. Now design a RC snubber and connect in to the circuit. Assume the series (leakage) inductance of the transformer is 0.695 mH and its core (magnetizing) inductance is 0.183 H. Observe the same voltages and note any similarities and differences.

Another popular type of snubber is an RCD snubber. RCD stands for resistor, capacitor, and diode. One good use for an RCD snubber is as a voltage clamper. Here’s the circuit:

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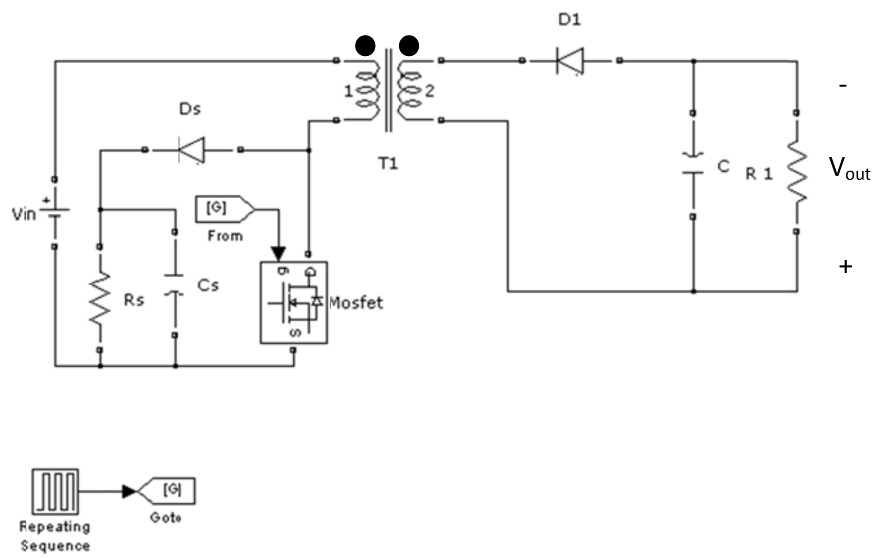

Circuit 4 Flyback converter with RCD snubber

While other types of snubbers are designed to do things like reduce ringing in a circuit or minimize power disspated by the FET, this one's sole purpose is to "clamp" the voltage across the switch at a certain level. That level is determined by the following relationship:

$$V_{clamp} = \frac{V_{out} * n_1}{n_2} + V_{in}$$

4. What is V_{clamp} for your snubber?

The next thing you need to determine is the peak value of the switching current. This can be easily found by analyzing a simple RL circuit.

5. Draw the equivalent circuit of the left-hand side of the flyback converter, not including any snubber, when the FET is on. Include the on-resistance of the FET you chose.

6. Assuming there's no current through the transformer when the switch is turned on, find the current through the FET at the instant the switch is turned off. Be careful as to which inductance value you use for this part.

Now you know everything you need to determine the value of C_s.

7. Use the following equation to find C_s. See you lab instructor if you'd like to see the derivation. ΔV is the amount of ripple you'll allow on your snubber capacitor. You choose that value.

$$C_{s,min} = \frac{L_s * {I_{peak}}^2}{\Delta V(\Delta V + 2V_{DC})}$$

8. Implement your RCD snubber and comment on the results.