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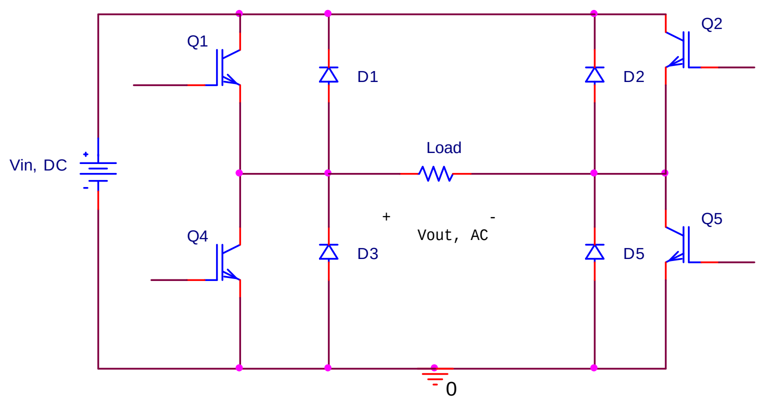
Lab 8: Pulse-Width Modulation

Pre Lab

Review of single phase inverters:

1. Following is the schematic for a single-phase H bridge inverter. Briefly describe its operation in 180^0 modulation mode. Include things like which IGBTs are on when and what the output voltage waveform looks like.



Circuit 1 Single phase H-bridge inverter

Uniform Pulse-width Modulation:

Up to this point we've only considered inverters working in 180^0 conduction mode, where a simple square wave is produced. As we saw in Lab 4, those square waves contain lots of harmonics that make the output power quality poor. In lab 4 we saw that one good way to get rid of those harmonics was with a filter. If you'll remember, though, there are a couple of big problems with only using filtering to get rid of harmonics: power losses, and component size. It look rather large L's and C's to filter out all those harmonics, and we didn't even get them down as much as is required to put power onto the grid.

Before we see what PWM can do for us, let's see how it works. The pulse-widths that PWM refers to are those of the gating signals. Instead of leaving the gating signals on for an entire half cycle as we've done before, now we'll apply a "train of pulses" to each IGBT. The IGBTs will still operate in pairs as they did before.

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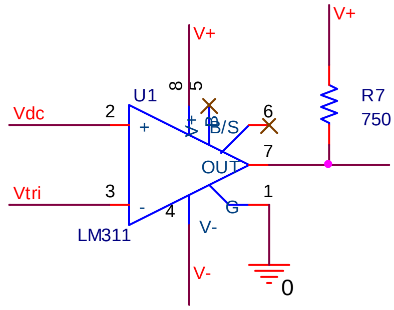
There are different ways to form that pulse train, one of which is with a triangle wave and a DC voltage. This type of PWM is sometimes called Multiple PWM or Uniform PWM. Consider the following circuit:



Circuit 2 Uniform PWM pulse train generator

The signal at the inverting input, Vtri, looks like this:

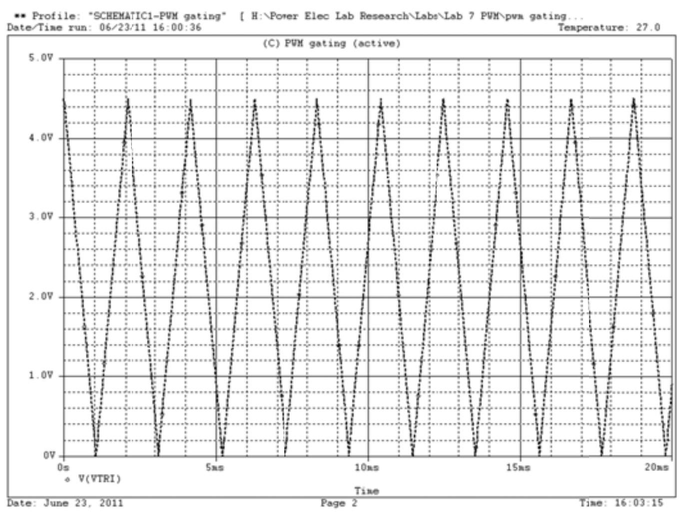


Figure 1 Vtri

For those of you who haven't seen one before, the LM311 in Circuit 2 is a comparator. When the voltage at its "+" input is greater than the voltage at its "-" input, the output is V+. Otherwise the output is 0V.

1. With that in mind, sketch the output voltage if Vdc is a constant 3V. Use the space directly below Figure 1.

2. How would the pulses change if Vdc were increased to 4V? Circle one:

   They'd be wider   They'd be narrower   They'd increase in frequency

3. How would the rms output voltage of the inverter change if Vdc were increased to 4V? Circle one:

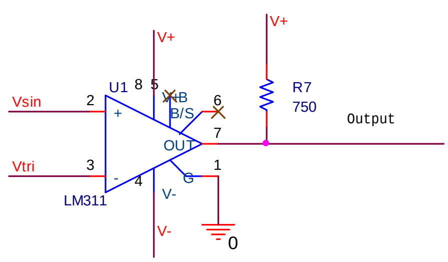
   Increase   Decrease   No change

Sinusoidal PWM

A more popular (and more useful) type of pulse-width modulation uses a triangle wave and a sine wave. This is called sinusoidal PWM (SPWM). We'll spare you the Fourier analysis and just tell you that this type of PWM is very useful because it does a better job of pushing lower-order harmonics to higher frequencies, where they're easier to filter out.

Another key benefit of SPWM is that if the grid is used as the sinusoidal signal, the inverter output will be synchronized with the grid. This also serves as a safety feature for a lot of wind turbines. If the turbine's inverter doesn't sense the grid's sine wave, it turns the turbine off. If the grid's signal isn't there, something must be wrong with the grid, therefore people will be out working on it. This keeps wind turbines from energizing the grid and potentially hurting a worker who's working on the system.

Consider the following circuit:



Circuit 3 SPWM comparator

This time Vtri has no DC offset.

1. Sketch the output voltage of Circuit 3 under Figure 2.

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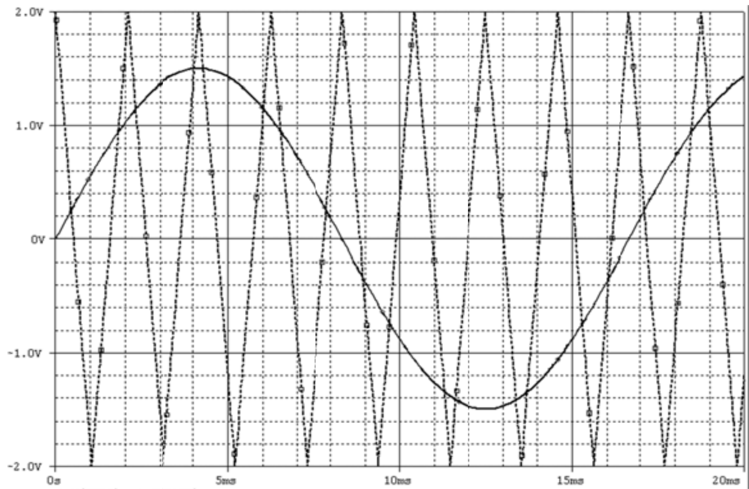
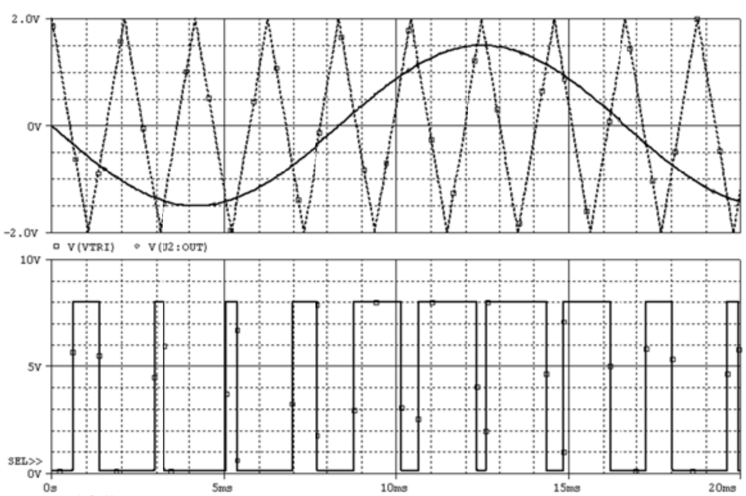


Figure 2 Vtri and Vsin

The waveform you just sketched could be the gating signal for one set of IGBTs. However, notice that the sine wave we used as input to the comparator went through a complete cycle and there were gate pulses throughout that whole cycle. Each set of IGBTs can only operate for half of a cycle, otherwise we'll short the input source and cause problems.

What would the output of Circuit 3 look like if the sine wave were shifted 180^0? Like this:



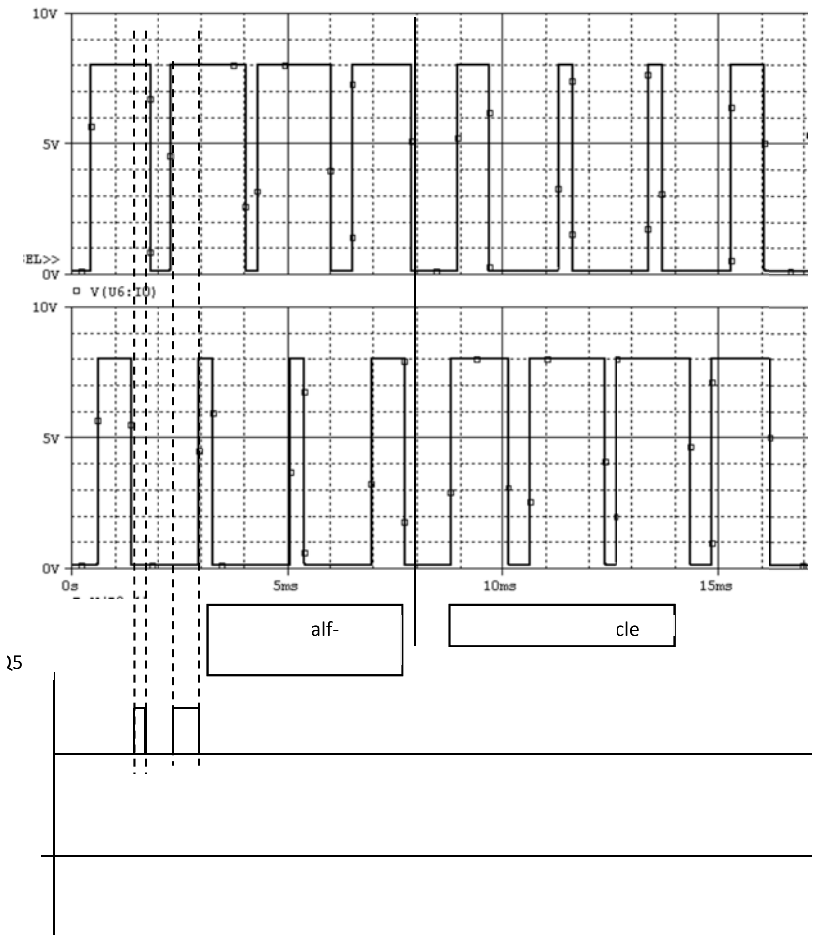
inputs

ltage

Figure 3 Comparator output voltage

Similarly, this could be the gating signal for the other set of IGBTs. But, like before, each set of IGBTs can only operate for half the cycle. But there's a simple solution! As you'll see during the lab exercises, we can use some simple logic to avoid shorting the source. For now, we'll just say that two "vertically aligned" IGBTs cannot operate at the same time.

2. With that in mind, sketch the gating signals on the axes provided. Don't worry about the magnitude of the gate pulses; we're just concerned with the pattern right now. The first two pulses have been drawn for you.



Lab Exercises

Uniform Pulse-Width Modulation

Here's the first circuit you need to construct (read on before you build it):

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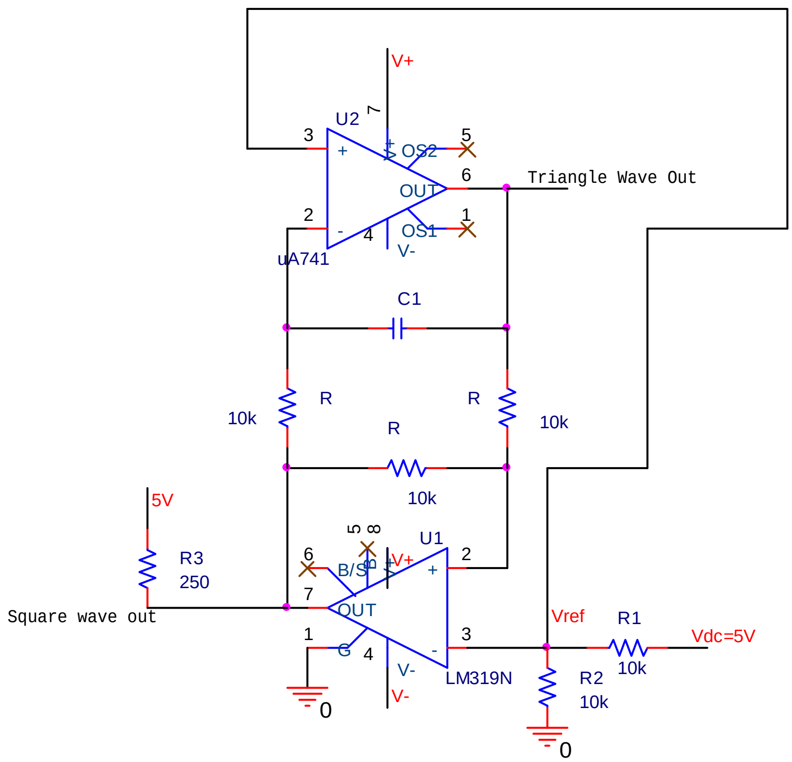

Circuit 4 Triangle Wave Generator

For those of you who are curious, this is a Schmitt Trigger whose square wave output is fed through an integrator. Since the integral of a constant is a ramp, we get a triangle wave out.

1. One of the most important characteristics of a PWM inverter is its carrier frequency (triangle wave frequency). You can set the carrier frequency of your circuit by setting the value of C1. The formula for the triangle wave frequency for Circuit 4 is:

$$f = \frac{Vdc}{4RC_1(V_{th} - V_{tl})}$$

$$V_{th} = 2V_{ref} - V_{square,low}$$
$$V_{tl} = 2V_{ref} - V_{square,high}$$

Use the given formula to pick C_1 to set the carrier frequency to a frequency of your choosing. Note the value you chose here.

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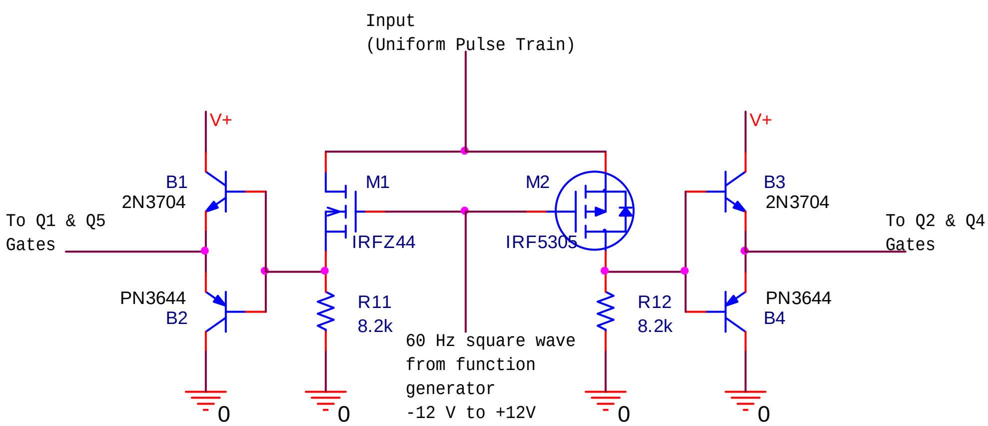
2. Using your power supply for the necessary voltages, build Circuit 4 and have your lab instructor verify its proper operation. The voltage at "Triangle Wave Out" should by a symmetrical triangle wave with V_{min} = 0 and V_{max} = 4.5 V (approximately). It should run at your chosen carrier frequency.

3. Build Circuit 2 (from pre-lab). Part one gave you a nice triangle wave to use as "Vtri." Use the DC power supply on the bench as "Vdc." The output of Circuit 2 should be a continuous train of pulses that go between 0 and the high rail of your homemade power supply. Recall what you did in the pre-lab and see if varying Vdc has the effect you though it would. DON'T LET Vdc GO TO 0 OR ABOVE THE MAX OF YOUR TRIANGLE WAVE, you'll fry your comparator if you do. Don't worry if the output is noisy, that's to be expected.

4. Finish off your circuit by adding Circuit 5 to the mix.



Circuit 5 IGBT Gate Driver

The outputs of Circuit 5 should be pulse trains that are 180^0 out of phase with each other. You should be able to watch both of them on scope (not connected to the IGBT gates), vary Vdc, and see the widths of the pulses change. Again, don't worry if it's noisy or jumps around on the screen a lot.

5. Now connect your gate driver circuit to the appropriate IGBT gates. DO NOT tie your circuit ground to the ground at the "Switching Control" of the Chopper/Inverter module. **Disconnect the 9-pin cable between the Chopper/Inverter and the DAC**.
6. Turn on your circuit and adjust Vdc so that it's 1.5V.
7. Determine, as accurately as you can, the actual frequency of the square wave from the function generator.
8. In the harmonic analyzer, change the "fundamental frequency type" to "user." Enter the frequency of the square wave as the fundamental frequency.
9. Take a screenshot of the voltage harmonic profile and compare it to the harmonic profile for 180^o modulation, shown below.

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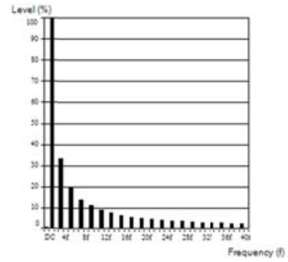
Harmonic Analyzer



Fundamental Frequency : 60.00 Hz

Distortion : 43.2 %

DC : 0.9

Harm.	Level (%)	Harm.	Level (%)	Harm.	Level (%)	Harm.	Level (%)
1 f	100	11 f	9.1	21 f	4.8	31 f	3.3
2 f	0.1	12 f	0.1	22 f	0.1	32 f	0.1
3 f	33.3	13 f	7.7	23 f	4.4	33 f	3.1
4 f	0.1	14 f	0.1	24 f	0.1	34 f	0.1
5 f	20	15 f	6.7	25 f	4.1	35 f	3
6 f	0	16 f	0.1	26 f	0.1	36 f	0.1
7 f	14.2	17 f	6	27 f	3.7	37 f	2.8
8 f	0.1	18 f	0	28 f	0.1	38 f	0.1
9 f	11.1	19 f	5.3	29 f	3.5	39 f	2.7
10 f	0.1	20 f	0.1	30 f	0.1	40 f	0.1

10. Vary V_{dc} and comment on how the output changes.

<u>Sinusoidal PWM</u>

1. Make the necessary changes to your triangle wave generator so that it matches Circuit 6.

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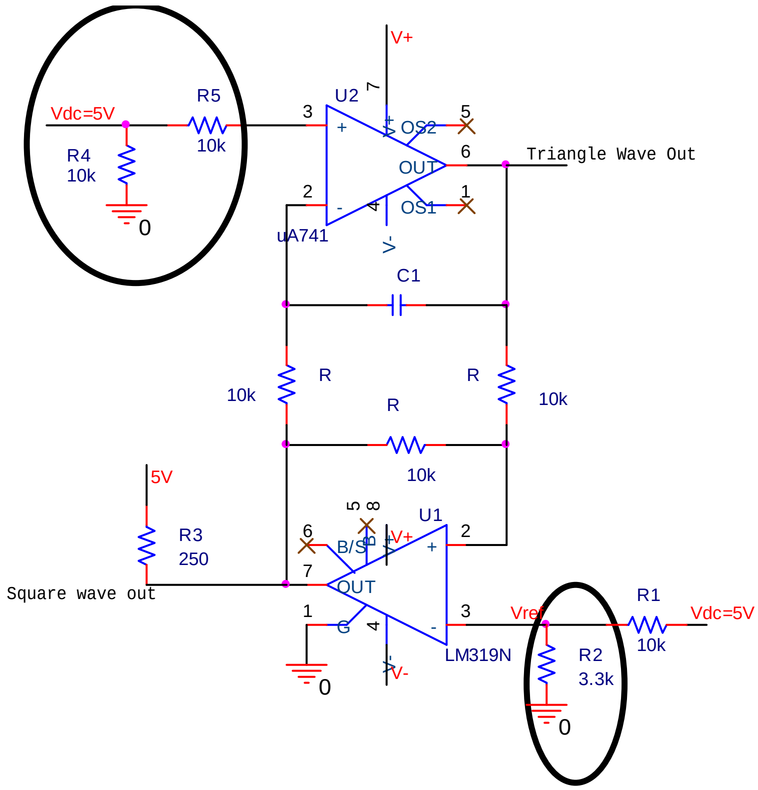

Circuit 6 Triangle wave generator, no DC offset

"Triangle Wave Out" should now be a symmetrical triangle wave that goes between -2V and +2V at your chosen frequency. This signal is called "Vtri" on the rest of the schematics.

Recall that Sinusoidal PWM (SPWM) compares a triangle wave reference signal with a sine wave. As discussed in the pre-lab, we'll get the sine waves straight from the grid. The way we'll be implementing SPWM requires two sine waves that are 180^0 out of phase.

2. Build a circuit that takes 120 V_{rms} from the grid as the input, and outputs a 1 V_{rms} sine wave that's 180^0 out of phase from the input.

3. Using the circuits you built in the previous two steps, construct Circuit 7. The outputs of Circuit 7 should look similar to your answer to pre lab question 1 (SPWM section) and Figure 3.

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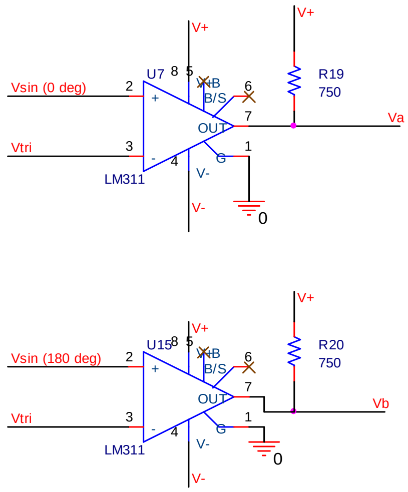
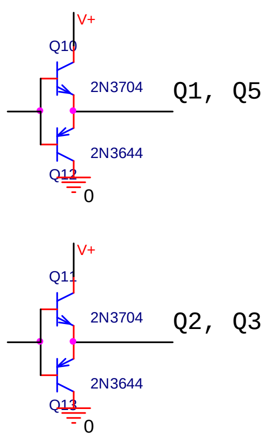


Circuit 7 SPWM square wave generators

4. Design and implement the logic circuits necessary to provide the actual gating signals to the IGBTs. The output of one logic circuit will provide gating signals to Q1 & Q5, and the other will provide the gating signals for Q2 & Q4. Include a schematic of your logic circuit in your report.

5. Attach the following totem pole gate drivers to the outputs of your logic circuits. The outputs of the gate drivers should match Figure 4.



Circuit 8 Totem pole gate drivers

Figure 4 SPWM gating signals

6. Connect the outputs of Circuit 8 to the appropriate IGBT gates. This time, tie the ground at the IGBT gates to the ground of your pulse train generator circuit.
7. Using a 15V_{dc} input, run your single-phase inverter with your SPWM gating circuit and a 200Ω load. Take a screenshot of the output voltage and of the harmonic profile. Comment on what you see and compare these results to what you saw with uniform PWM.

8. Vary the amplitude of the reference sine wave. Don't let its amplitude get larger than that of the triangle wave. What changes do you see in the output of the inverter?

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9. Theory says that SPWM shifts all harmonics below 2p-1 (p=number of pulses per half-cycle) up to around the carrier frequency. Is that true for your output voltage? Why would that be advantageous?

10. Compare the harmonic profiles of SPWM and UPWM (which you did I the first part of the lab). Which would you use if you were building an inverter and why?