University of North Carolina-Charlotte
Department of Electrical and Computer Engineering
ECGR 3157 Electrical Engineering Design II Fall 2013

Lab 1
Impedance Analysis and Power-Electronic System Design

Due: September 16, 2013

GOALS: Develop a greater understanding of dynamics
Begin to learn the principles of circuit design
Begin to learn about power-electronic systems, which are at the heart of mechatronic systems

In this lab, you will be designing and building a fluorescent lamp ballast. The overall system will look like so:

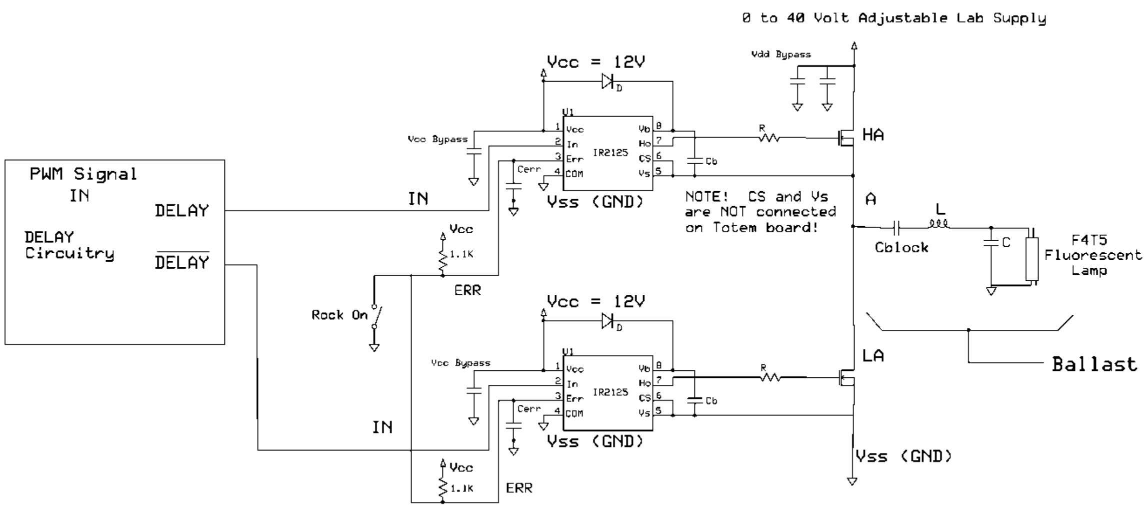
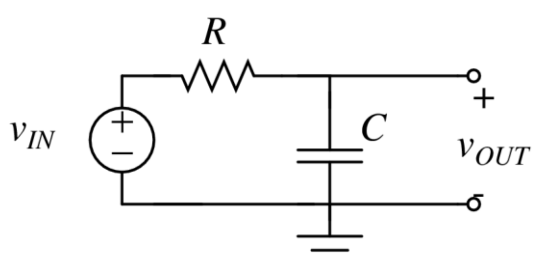


Figure 1: The Fluorescent Lamp Ballast Circuit

In this lab, you will be designing and constructing the components of the circuit above. You will also be answering a number of questions about the circuit and its operation.

EXERCISE 1: Interfacing with Dynamic Systems

In class, we've looked a lot at the circuit shown below. To begin, we will construct this circuit.



Using your notes, you should be able to write out the time-domain response for this circuit. Construct the circuit shown above using the function generator and a set of components that yield a time constant of approximately 100μs.

Assume the input is of the form

$$v_{IN} = V_{IN} \cos(\omega t)$$

To generate this, setup the function generator like so:

- Waveform: Sine
- Frequency: 10Hz
- Offset: 0V
- Amplitude: 2V

Please answer or do the following:

1) Using the parameters (i.e. frequency, amplitude, etc.) defined above express the output of the function generator in the following three ways:
    a. Using a traditional cosine expression
    b. Using complex exponential notation
    c. Using phasors
2) Measure the output voltage across the capacitor using the oscilloscope (Make sure that it is AC coupled). Provide a sketch showing the input voltage and the output voltage on the same set of axes. Express the measured output voltage in the following three ways:
    a. Using a traditional cosine expression
    b. Using complex exponential notation
    c. Using phasors
3) Use circuit analysis to predict the amplitude and phase of the output voltage. Compare this result to the measured result from Question 2. If there is a difference, please explain.
4) Change the frequency to 500Hz and then to 5kHz. At both frequencies, express the input and the output in the following ways:
    a. Using a traditional cosine expression
    b. Using complex exponential notation
    c. Using phasors

    At both 500Hz and 5kHz, calculate the predicted amplitude and phase of the output voltage. Again, if there are any differences, please explain. Provide sketches of the input and output voltage at both frequencies.
5) At 5kHz, change the waveform type to square. Does the measured amplitude and phase match the actual amplitude and phase of the output voltage? Explain the difference.

Note that the easiest way to measure phase shift is to use the following expression:

$$Phase\ Shift = \frac{Time\ Shift}{Period} 360^\circ$$

6) Explain the expression used for measuring phase shift.

EXERCISE 2: Understanding the Switching Amplifier

In class, we have talked extensively about the totem-pole circuit using the MOSFETs. In this exercise, you are going to experiment with the MOSFET to understand its operation. As we discussed in class, driving a MOSFET so that it acts like a switch is a bit more challenging than it might sound. Several reasons for the difficulty are as follows:

- First, the driver circuit should tum the MOSFET on or off quickly. That is, the driver should keep the MOSFET out of a dissipative state (i.e. nonzero voltage across it and nonzero current through it) to the greatest extent possible.
- Also, recall that the operation of the MOSFET is set according to its gate-to-source voltage. Difficulty arises if the source lead is not connected to a fixed voltage node in the circuit. We'll explore this issue in the next exercise.

Construct the single MOSFET circuit with IR2125 driver shown in Figure 2. Rload should be the power resistor given to you in your component kit. The following components should be used:

- $C1 \approx 0.1\mu F$ (Should be available in the lab)
- $Ce \approx 0.015\mu F$
- $Cb \approx 1\mu F$ or $0.82\mu F$
- Rgate on the order of 10 Ohms or so (Should be available in the lab)

For the designated capacitors, use the red metal-film capacitors that were given to you in your component kit. Drive the input line connected to pin 2 of the IR2125 from your function generator using a waveform with the following specifications:

- Waveform: Square
- Frequency: 30kHz
- Offset: 1.25V
- Amplitude: 2.5V

The resistor Rload should be the highest resistance power resistor provided in your component kit.

Please answer the following questions:

1. On the same set of axes, sketch the voltage al the drain and the voltage at the gate. Explain the relationship between the two waveforms in terms of the operation of the MOSFET. Please provide a technical explanation (i.e. I'm looking for something more meaningful than "One is high when the other is low.")
2. Why can't you measure the voltage across Rload directly with an oscilloscope? To answer this, think about what is true about the oscilloscope probe.
3. What is the time-averaged voltage across Rload? To determine this, consider a single switching period.
4. Does your MOSFET need a heat sink? Explain why or why not. To answer this question, you will have to think about why a heat sink would be required in any application.
5. If Rload was replaced with an inductor, the MOSFET would likely fail when the MOSFET turns off. Why? To answer this question, sketch the circuit with an inductor and carefully consider the constitutive relation for an inductor, i.e. $v_L = L di_L/dt$.

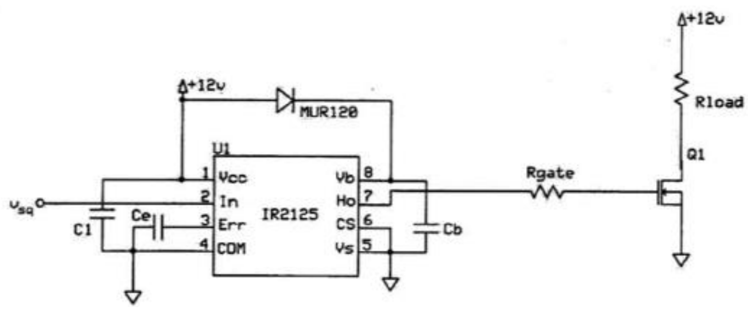


Figure 2: Simple Power Amplifier

EXERCISE 3: Designing and Building a Delay Circuit

To build the complete switching power amplifier with two MOSFETs, we need to make sure that we open one MOSFET before closing the other. In order to do so, we must design a circuit that creates proper control signals for the MOSFETs.

1. Figure 3 shows a typical delay circuit. The signals DELAY and #DELAY (#DELAY signifies the inverted version of DELAY) can be used to control a pair of switches so that we "break" or open an active switch before "making" or turning on another switch. Please answer the following questions about this circuit:

   a. The circuit in Figure 3 creates a delay using two RC circuits. One of those RC circuits charges its capacitor faster. Which one? One of the RC circuits discharges its capacitor faster. Which one? Explain your reasoning in both cases.

   b. Let's consider one of the RC circuits for a moment. Assume that the diode is removed. At time t = 0, we apply a step input with a value V_{final}. Immediately prior to time t = 0, the capacitor is charged to the voltage $V_{initial}$. Please do the following:

      - Write a differential equation that can be used to find the capacitor voltage as a function of time.

      - Solve the differential equation. In order to solve this problem, find the transient solution and guess a steady-state solution. Add the transient solution and the steady-state solution. The final solution is in your notes.

   c. Using your result from part b, write an equation that describes the charging process for the capacitor in the upper leg of the circuit. Write a similar equation for the discharge of the capacitor in the lower leg of the circuit. These equations should include actual initial and final values for the voltages on the two capacitors. In your notes on this subject, we noted a few things that will help here:

      - Because of the diodes, the initial values of the voltages on the capacitor will be either ~0.6V or ~4.4V, depending on the setup. You'll have to think about how to use this.

   d. Assuming that v_4 transitions from HIGH to LOW when v_3 reaches 1V, select a time constant that will ensure that it takes approximately 750ns for v_3 to reach 1V.

e. Assuming that v_8 transitions from LOW to HIGH when v_7 reaches approximately 1V, select a time constant that will ensure that it takes approximately 750ns for v_7 to reach 1V.

2. Construct the circuit shown in Figure 3 using your calculated time constants and a 74LS04. **Choose C = 1nF and then choose a value of R that gives approximately the right delay.** The actual delay is the time between a high-to-low transition at DELAY and a low-to-high transition and #DELAY and vice versa. The easiest way to measure the delay is to simultaneously measure v_3 and v_4 and to then simultaneously measure v_7 and v_8. **Ultimately, your delay should lie somewhere between approximately 700ns and 1 microsecond. The actual value does not matter. If your delays are initially outside of this range, adjustment should be easy if you use your intuition. For instance, if one of your delays is slightly less than 750ns, you should try to increase R and keep C constant.**

   In your report, please show the following two plots with the appropriate time measurements labeled:
   - A high-to-low transition at DELAY and the corresponding low-to-high transition at #DELAY
   - A low-to-high transition at DELAY and the corresponding high-to-low transition at #DELAY

   When building, make sure to power your NOT gates to an appropriate logic-level voltage.

   The course website has a document that describes how to measure the delays.

3. Explain why it makes sense to measure the delays by simultaneously measuring v_3 and v_4 and v_7 and v_8.

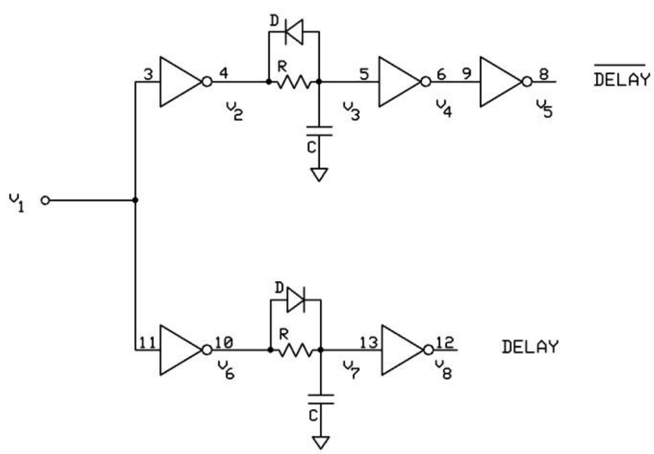


Figure 3: Delay circuit

EXERCISE 4: Constructing a Switching Power Amplifier

Now, let's build a full totem-pole circuit like the one shown below:

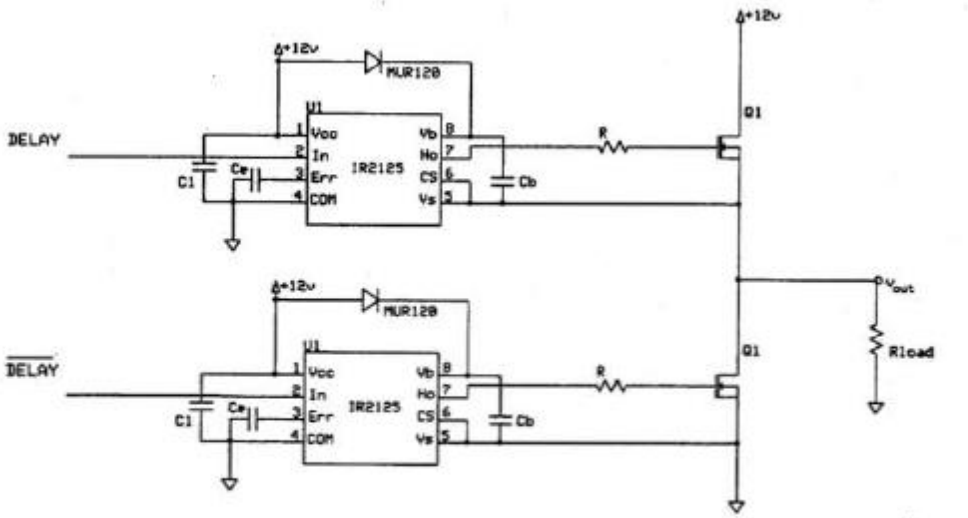


Figure 4: Full Switching Power Amplifier

Please do or answer the following:

1. Construct the circuit shown in Figure 4. For Rload, use the power resistor that you were given in your component kit. Connect the DELAY and #DELAY lines from your delay circuit to the appropriate inputs in Figure 4. Setup your function generator to provide the following:

    - Waveform: Square
    - Frequency: 36kHz
    - Offset: 1.25V
    - Amplitude: 2.5V

2. Sketch the voltage across Rload, the voltage at pin 7 of the upper 2125, and the voltage at pin 7 of the lower 2125. Label the plots appropriately. Explain in detail why the waveforms appear as they do.
3. Use your results to explain how the IR2125 turns on the MOSFETs. Provide a detailed explanation.

EXERCISE 5: Design Problem Warm-Up (Does not need to be done in Lab)

As we've discussed in class, a practical ballast looks something like so:

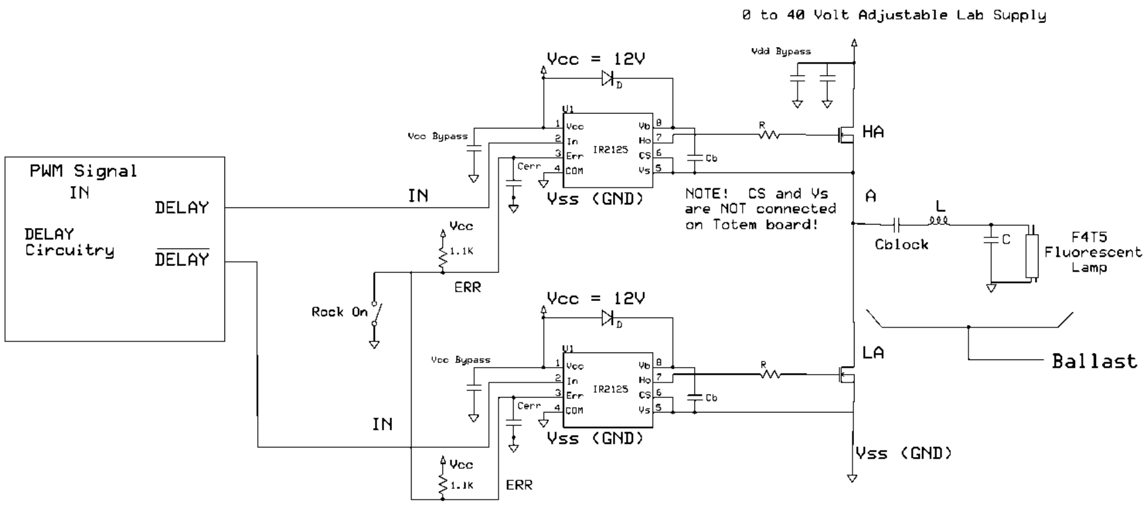


Figure 1: The Fluorescent Lamp Ballast Circuit

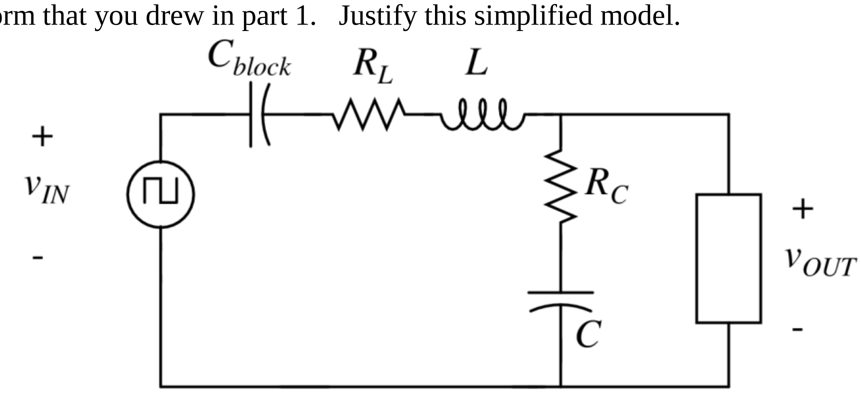
In this exercise, we'll analyze this circuit. This will help us with the design to be performed in the next exercise. Let's begin by assuming the following:

- The 0 to 40V adjustable lab supply is set to a voltage V

Please answer the following questions about this circuit:

1) Assuming that the FET labeled HA is on from time 0 to time 0.5T and that the FET labeled LA is on from time 0.5T to T, sketch the voltage at point A (the mid-point of the totem pole) over a single period. Label key points on the voltage and time axes. Explain your answer. In this problem T stands for the switching period.

2) As we said in class, this circuit can be redrawn as shown below. The input source is the waveform that you drew in part 1. Justify this simplified model.



3) The simplified circuit drawn in part 2 cannot be analyzed using impedance analysis. How must we view the input source if we wish to use impedance analysis? Why?

4) In Circuits 2 (and in lecture), we said that the waveform you found in part 1 could be viewed as a sum of sine waves, like so:

$$v_{IN} = V_{DC} + \mathrm{V}_1\sin(\omega t) + \mathrm{V}_3\sin(3\omega t) + \mathrm{V}_5\sin(5\omega t) + \cdots$$

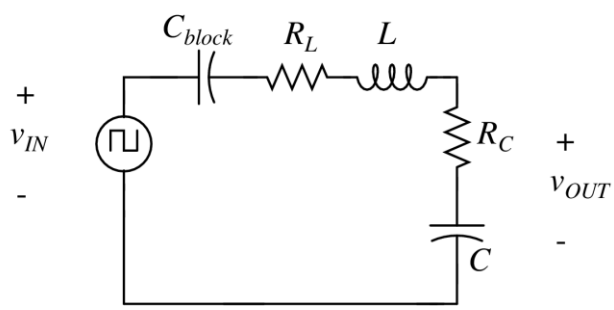
where V_{DC} is the average value of the waveform, and the amplitude of the *n*-th harmonic is:

$$V_n = \frac{2}{T}\int_0^T v_{IN}(t)\sin(n\omega t)dt$$

Find the value of V_{DC} and the value of V_n in terms of *n* and V. To receive full credit, you must show your work.

5) The purpose the capacitor $\boldsymbol{C_{block}}$ is to ensure that no DC voltage appears across the lamp. We can prove this using an appropriate model. Use your answer from part 3 to analyze the circuit at DC. Show that with the capacitor $\boldsymbol{C_{block}}$ in place, the voltage across the lamp is 0 at DC. In your analysis, assume that the lamp can be approximated by a resistor R with a very large resistance, potentially as high as several megaohms. To make this analysis simple, think carefully about the impedance of each individual component at DC. Note that you do not need to know the numeric values of any of the individual components in order to perform this analysis.

6) At frequencies close to the resonant point, we noted that the parasitic resistances of the individual components become very important. At frequencies near resonance, and before the lamp strikes, the circuit appears as follows:

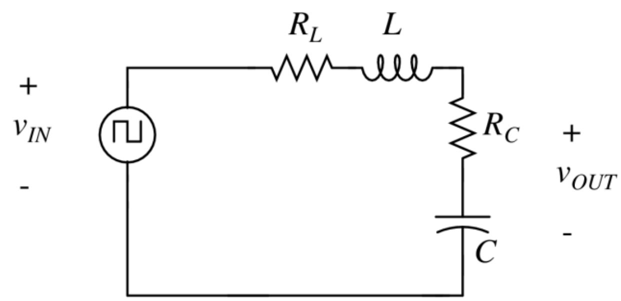


Use impedance analysis to determine the complex magnitude (i.e. phasor) of the voltage v_{OUT}.

7) In order to make the design problem simple, it's desirable for the capacitor C_{block} to affect only the DC behavior of the circuit and thus have a negligible effect at resonance. Consider the total capacitance in the circuit to be C_{total}. Show that you can select a value for C_{block} so that C_{total} is less than 1% different than C.

   Since C_{total} is less than 1% different than C, it is a reasonable engineering approximation to say that $C_{total} \approx C$. Use this result to simplify the transfer function that you found in part 6.

8) Now the circuit can receive one final simplification as shown below



Using impedance analysis, write an expression for the complex magnitude of the output voltage in terms of R_L, R_C, C, and L. Show that this is the same result you found in part 7 by assuming that C_{block} is negligible.

From this point forward, assume that C = 0.05$\boldsymbol{\mu F}$, V = 40 Volts, and that the frequency of the square wave is 40kHz.

9) Determine appropriate values for $\boldsymbol{C_{block}}$ and $\boldsymbol{L}$ assuming that maximum value of the output voltage should occur at approximately 40kHz.

10) Determine an expression for the magnitude of $\underline{\boldsymbol{V_{OUT}}}/\underline{\boldsymbol{V_{IN}}}$ in terms of R_L, R_C, C, and L.

11) Using your expression for the magnitude of $\underline{\boldsymbol{V_{OUT}}}/\underline{\boldsymbol{V_{IN}}}$, determine the magnitude of the output at the fundamental frequency (i.e. 40kHz) and at the third and fifth harmonic frequencies. Assume that $R_L = 3\Omega$ and $R_C = 2\Omega$. Use the values of C and L that you determined or were given previously.

12) Using your results from part 11, justify our approximation that the output voltage will look approximately like a single sine wave.

13) The inductor core has an A_L value of 100nH. How many turns of wire will be required?

EXERCISE 6: Design Problem - Designing the Fluorescent Lamp Circuit (Does not need to be done in Lab)

Now, we need to design the fluorescent lamp ballast circuit using the design shown in Figure 1. Here are our basic specifications:

- The adjustable supply voltage is 40V
- Minimum voltage needed to strike the lamp: 300V
- The initial frequency is 36kHz
- Once the lamp strikes, the current through should be less than 100mA peak. Recall that the lamp looks like a resistor with an approximate value of 500 Ohms.

To complete the design, take the following approach:

1) Look at the capacitor values on the available components section of the web site and select C, C_{block}, and L. Use only one capacitor for C and only one capacitor for C_{block}. I recommend that

you select C_{block} and C so that the difference between the impedance of C and C_{block} is as large as possible at 36kHz.

2) Determine how much voltage gain the circuit must provide at resonance in order to make the lamp strike.
3) Analyze the circuit before the lamp strikes, assuming that both the inductor and the capacitor have series resistance. Determine the peak value of the magnitude of $\underline{\boldsymbol{V_{OUT}}}/\underline{\boldsymbol{V_{IN}}}$ using your expression from the previous exercise. For the value of R_C, use the capacitor datasheet available on the website and the approach used in class. When determining the value of R_C, use the worst case value, assuming that we would like to operate over a temperature range up to 100 degrees C. To do so, you will need to use the % dissipation curve vs. temperature. Determine the maximum allowable value of R_L that will allow the lamp to strike. The Matlab script that will help you with this part is found on the course web site.
4) Once the lamp strikes, the series resistance of the inductor and capacitor become somewhat negligible and the lamp resistance becomes dominant. Once again, use Matlab to determine the peak value of the voltage across the lamp. Use this value to determine the current. If the current is too large, suggest an approach that can be used to reduce the current once the lamp has struck.
5) You must select a core on which to wind the inductor. You have the following cores from which to choose:

    - Micrometals Iron Powder T400-52
    - Ferroxcube Ferrite P36/22-3C81-A1000

    Data on these cores is available on the website. To select an appropriate core, use the approach presented in lecture. The core that you select should be the one that seems to be the most robust. Explain your decision and show all of your calculations. Note that the manufacturer of the ferrite core measures B in Tesla, and the manufacturer of the iron powder core measures B in Gauss. Recall that 1T = 10,0000 G. Pay careful attention to the geometric units, and make sure that you calculate the peak B-field using standard SI units (i.e. rad/sec, meters, and Volts).
6) For monitoring and control purposes, we wish to have a voltage divider across the lamp that will allow us to safely monitor the output voltage. Design a voltage divider whose output voltage will be less than 10V when the output voltage is 300V. This voltage divider should draw a current less than 300 microA.

In your lab report, please include the following:

- Detailed design calculations, along with descriptions of the calculations. You must use complete sentences to describe what you're doing.
- Relevant plots
- A final table summarizing all of the key component values (C, C_{block}, L, number of turns, voltage divider values, core choice)

Once you are complete, you can pick up cores, wire, and capacitors from my lab. ***You must bring your calculations with you to pick up these components.***

EXERCISE 7: Building a fluorescent ballast

You will now build the fluorescent lamp ballast that you designed previously. The circuit should follow the schematic shown in Figure 1.

When you wind your inductor, keep the following in mind:

- The wire is covered in a non-conductive shellac. This will need to be removed from the ends of the wire with sandpaper in order to make electrical connections to the wire. You will find sandpaper in the bottom of the set of resistor drawers in Room 2148.

During the testing, please do the following:

- Power the IR2125 drivers from the 12 V power supply.
- Power the delay circuit from the 5V power supply.
- Replace the MOSFETs (i.e. the 0-40V adjustable supply in the schematic) with a 12V supply available in the lab. Make a dedicated connection for this**. In other words, use one set of cables for power to the drivers and another set of cable for power to the MOSFETs.**
- Provide a waveform from the function generator to the delay circuit. Use the following specs:
    - WAVEFORM: Square
    - OFFSET: 1.25
    - FREQUENCY: 40kHz
    - AMPLITUDE: 2.5V
- Place C_{block}, C, and L on your breadboard, and connect them appropriately.
- Make sure to include the voltage divider that you designed, and ***make sure that one side of the 30kOhm resistor is connected to ground.***

Once the circuit has been constructed, measure the voltage across the 30kOhm resistor. You should see a small 40kHz sine wave across the resistor. Once you do, you are ready for your check-off.

EXERCISE 8: Understanding the Inductor (Does not need to be done in Lab)

Consider an inductor wound on the ferrite pot core such as the one that you might have wound in Exercise 7. *N* turns of wire are wrapped around the core.

a) Construct a magnetic circuit model including an MMF source and two reluctances.

b) Assuming that the μ (permeability) of the ferrite is much, much larger than the permeability of the air gap in the core, can you simplify your circuit model from part a?

c) Using the A_L value given in the datasheet for the ferrite core, what is the total reluctance?

d) A 1mH inductor has been wound on the core, and it is placed in a resonant circuit such as the one considered in this lab. A sinusoidal voltage with a peak value of 300V appears across the inductor at 30kHz. What is the peak flux flowing through the magnetic circuit?