

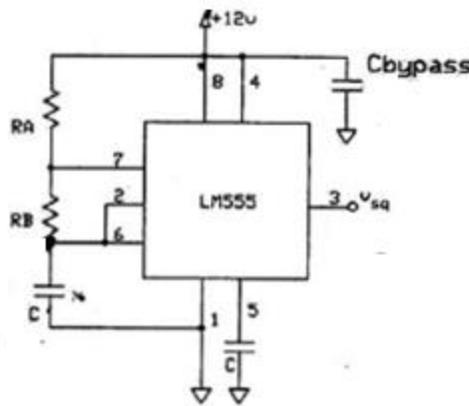
Lab 3: Power-System Components and Power Electronics

**Exercise 1: PWM Modulator**

In the first parts of this lab, you will construct a switching motor drive. To do so, you must first construct a PWM modulator. This requires you to construct a saw-tooth generator and a comparator. Let's start with the saw-tooth generator.

*Saw-tooth Oscillator.*

1. Consider circuit (e) shown below. Design and build a version of circuit (e) that creates a 30kHz square wave at pin 3 of the 555. Design the circuit so that C charges approximately four times longer than it discharges.
2. Place a scope probe on Pin 8 of the LM555. Briefly remove the 0.1  $\mu\text{F}$  bypass capacitors, and sketch the voltage that you measure on the scope. When finished, replace the bypass capacitors. Provide plots in your report.
3. How did the measured voltage change? Explain the action of the bypass capacitors – Please provide a technical answer and not "It's smoother now."
4. Without bypass capacitors, the frequency at the output of the LM555 might fluctuate. Explain.
5. Where should bypass capacitors be located physically? Why? Using schematics in your answer might help.
6. What values and properties do you want in a bypass capacitor?



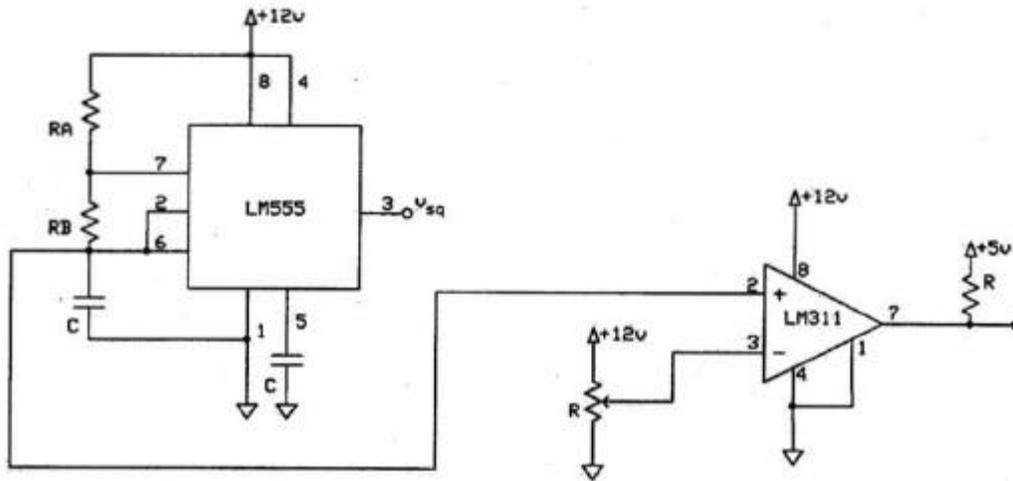
Circuit (e) Astable 555 timer

*Complete Pulse Width Modulator*

Now, let's build a complete PWM circuit. The schematic shown in (f) can be used as a PWM source. That is, the circuit in (f) can produce a square wave at the output of the LM311 comparator that exhibits a duty cycle determined by the setting of the pot. Do and answer the following:

7. Design and build (f) to develop a 30kHz PWM signal. Design the 555 circuit so that C charges approximately four times longer than it discharges. Generate the 5V at the LM311 output from the 5V supply at the bench. The pull-up resistor at the LM311 output should be several kOhms.

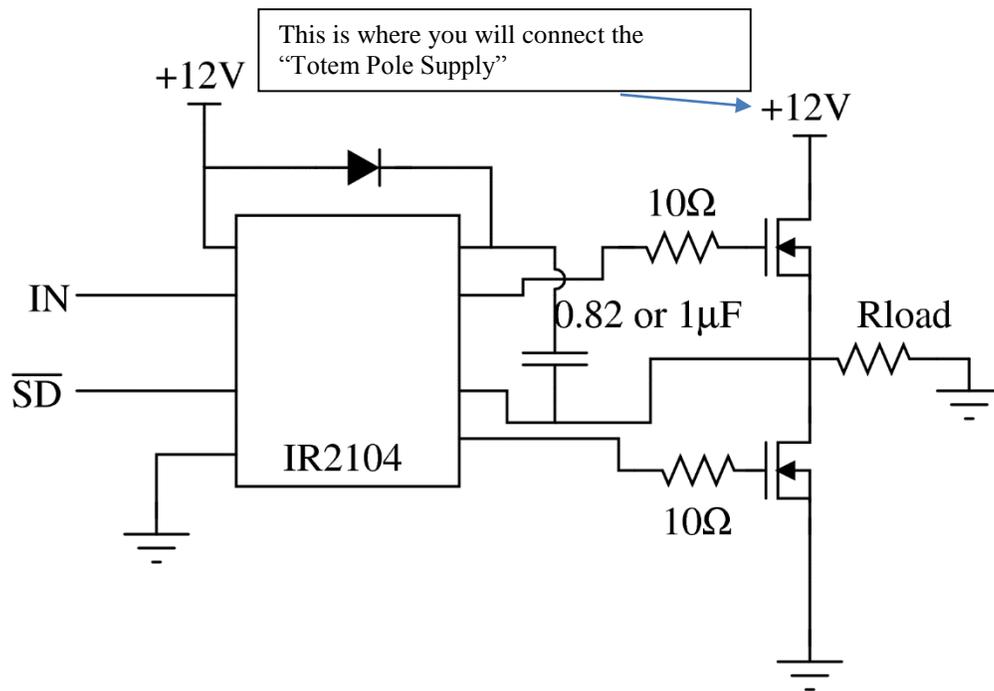
8. Explain how the LM311 creates a variable duty cycle square wave at its output.
9. What effect does increasing the value of the pull-up resistor have on the output? To answer this, you may need to try a large pull-up resistor, i.e. something on the order of several hundred kOhms. Why is this?
10. Does the switching frequency of this circuit depend on fluctuations in the 12V power rail connected to the LM555 (When answering, assume that the LM555 is connected to a separate 12V rail).
11. Does the duty cycle of the square wave at the output of the LM311 vary with fluctuations in the +12 volt rail connected to the potentiometer? (When answering, assume that the potentiometer is connected to a separate 12V rail).
12. If the voltage at Pin 3 goes outside of a certain range, the LM311 output will either be a constant 0V DC signal or a constant 5V DC signal. Why? In order to maintain a square wave at the output of the LM311, what range of voltages should be maintained at Pin 3 of the LM311?



Circuit (f): A PWM Modulator

## EXERCISE 2: Low-Pass Filters and Switching Amplifiers

Now, let's build a full totem-pole circuit like the one shown below. **Please note that this is nearly the same circuit you built in Lab 1, so you should already have all of the parts.**



Circuit (i): Switch amp

Please do or answer the following:

1. Construct circuit (i) above. For Rload, use your larger power resistors that you were given at the beginning of class. Connect IN to the output of the PWM modulator shown above (circuit f). Connect the  $\overline{SD}$  pin as appropriate according to the data sheet for the IR2104.
2. Sketch the voltage across Rload, the voltage at pin 7 of the IR2104, and the voltage at pin 5 of the IR2104. Label the plots appropriately. Explain why the waveforms appear as they do using your understanding of the MOSFET.
3. Replace the load resistor with an RC low-pass filter. Design this filter so that it has a bandwidth of approximately 100Hz.
4. With the low-pass filter in place, simultaneously measure both the voltage across the capacitor and the voltage at the mid-point of the totem pole. Vary the duty ratio. Explain the relationship between the two waveforms. Include appropriate plots in your report.
5. Remove your low-pass filter and travel over to the DC motor test station located in the Areva Power Laboratory. Please note that this station has the following components:

- Field Voltage Source
- Totem Pole Supply
- Triple Output Supply for your 555, 311, and IR2104
- DC Compound Machine
- Oscilloscope
- Tachometer (used to measure speed)

Please do the following:

- Make sure that the field voltage source is connected to terminals E1 and E2 on the motor.
- Make sure that the field voltage source is set to approximately 15V
- Power your 555, 311, and IR2104 from the Triple output supply as needed

- Before connecting the the “Totem Pole Supply” to your circuit, turn it on and verify that it’s set to about 25V.
- Connect the Totem Pole Supply as shown in the figure above. Make sure to also connect the ground to your circuit. **MAKE SURE THAT THE TOTEM POLE IS NOT ALSO CONNECTED TO THE +12V rail.**
- Connect the A1 terminal on the motor to the mid-point of your totem pole circuit.

Once you have checked and double-checked all of your connections, please do the following:

Step 1) Set the duty ratio to about 10%. Using the tachometer, record the speed.

Step 2) Repeat Step 1 for duty ratios of approximately 25%, 50%, 75%.

Step 3) At a duty ratio of approximately 50%, move the switch on the totem supply from “Volts” to “Amps.” This simply converts the display to show the current rather than the voltage. Note the current. Lightly grab the shaft of the motor. Record the current.

Step 4) At a duty ratio of approximately 50%, decrease the field voltage source to approximately 10V. Record the speed.

In your report, provide a detailed listing of all of your measurements. Please answer the following questions, keeping in mind the circuit model for the DC motor:

- What was the average voltage applied to the motor for each of the duty ratios above?
- Plot the speed and average voltage from Steps 1 and 2. Explain the shape of the curve using the DC motor circuit model.
- Explain why the motor did not respond to the 30kHz component of the voltage. Make sure to provide a detailed answer in terms of the models that we discussed in class.
- Using the motor circuit model, please explain why and how the speed changed when the field voltage was reduced.
- Explain why and how the current changed when you grabbed the shaft of the motor.

You built the same circuit in Lab 1, except that you used a “Delay circuit” instead of an IR2104. IR2104s are available in the bottom drawer of the cabinet in the lab.

### **Exercise 3: Using PWM to Construct a Stereo Amplifier**

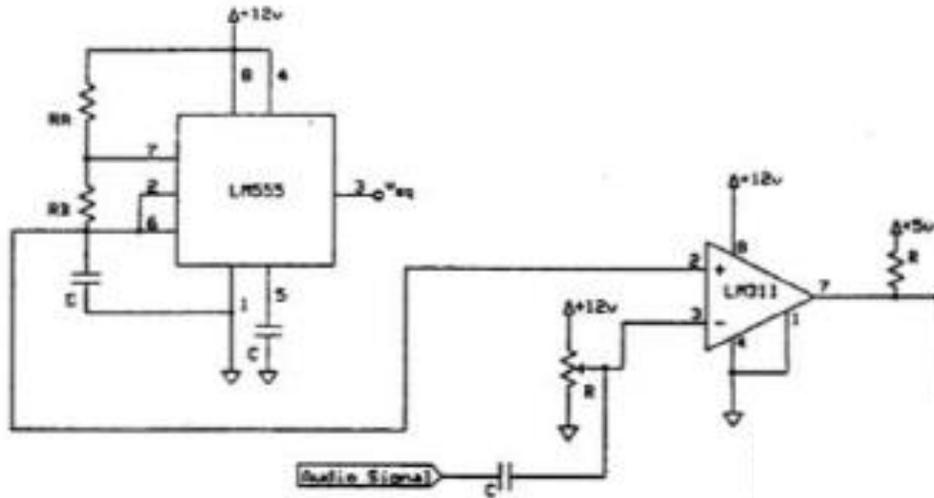
Now, let's use a PWM generator, a delay circuit, and a MOSFET totem pole to drive an audio speaker. Several speakers will be available in the lab. For this, please return to the regular lab (EPIC 2148).

Please do or answer the following:

- 1) Modify your LM311 circuit as shown below. Assume that the audio input is a 1V peak-to-peak sine wave at 1 kHz. Use a 1uF AC coupling capacitor to bring the audio signal into pin 3. Why is this capacitor necessary, and why does the value have to be relatively large? Answer using a circuit model.
- 2) Connect a speaker to the midpoint of the totem pole. Place a 220microF capacitor in between the speaker and the totem pole. Why is this necessary?
- 3) Set the DC level at pin 3 of the LM311 to 6V. Drive the coupling capacitor (where the label says "audio signal") with a one or two volt peak-to-peak sine wave at 1kHz. Carefully adjust the signal generator and check its output with an oscilloscope before making any connections to pin 3. When everything is connected, you should hear a sine wave tone coming out of the speaker. Why

are you hearing this? Explain carefully. To help think about the behavior of the DC motor and the low-pass filter.

- 4) Which audio amplifier (this one or the one from Lab 2) would be more desirable in a portable, battery-powered device?



#### Exercise 4: Characterizing a Power Transformer Part 1 – Data Collection

You have already completed this. If you would like to reread it, it was sent previously.

#### Exercise 5: Characterizing a Power Transformer Part 2 – Data Analysis

Now that you have obtained data, it's time to perform some basic analysis that will let you better understand how the transformer should be modeled when connected as a part of a larger system. In order to complete this activity, you are requested to load the data into MATLAB. All told you should have obtained 8 files during the first part of this exercise. These files should be named TEK0000.CSV through TEK0007.CSV.

Let's begin the process of analyzing the data so that we can justify our models. We proceed through this problem in 5 parts:

- Part 1: Preparing the data to be manipulated
- Part 2: Determining the turns ratio
- Part 3: Determining the magnetizing inductance and core-loss resistance
- Part 4: Determining the leakage inductance and winding resistance
- Part 5: Using your parameters to analyze the transformer under load

##### Part 1: Preparing the data to be manipulated

- a) Before using any of the data for analysis, we first need to better understand what we have acquired. Since we recorded analog values using our digital oscilloscope, it is clear that we have used an analog-to-digital (A/D) converter inside the scope. We first need to determine the sampling frequency of this A/D converter. Each of the CSV files recorded during the previous part contains 2500 samples.

In your report, please provide detailed answers to the following questions:

- Given that your total measurement window included 10 divisions at 25ms per division, what is the sampling frequency?
  - Given that the voltages and currents that you measured are all 60Hz waveforms, how many points (i.e. samples) are there in one period?
- b) Now, let's load the primary and secondary voltages during the open-circuit test and the primary current from the "loaded" tests. To do so, use the command `csvread` in MATLAB. Consult the MATLAB Guide on the website for help. Use the vectors `v1`, `v2`, and `i1` for the primary and secondary voltages and primary current, respectively.

As you should recall from the lab, the values of the voltages that you recorded on the oscilloscope are clearly not the same as the actual values applied to the transformer. In reality, you measured the actual voltages and currents using what are known as instrument transformers that scale down the voltages and currents to safe, isolated values. This is very typical. For instance, it is very common in a large system to scale down a 4.16kV bus voltage to 120V. To know the actual voltage, you need to know the conversion gain of the instrument transformers. We now compute these conversion gains in three steps:

*Step 1 – Remove the DC Offset:* One issue we have here is that our sensors have some DC offsets, meaning that there is some DC or average value in the measured signals that doesn't appear in the actual signals. To remove the offset, you should first plot one of the signals and prove to yourself that there is a small offset. Since the waveforms should be purely AC, think about how you could remove the average value from them. One helpful command in MATLAB is `mean`. Be sure to remember that the true average of any periodic waveform is defined as

$$X_{DC} = \langle x \rangle = \frac{1}{T} \int_0^T x(t) dt$$

In your report, please provide the following:

- A detailed and well-explained analysis showing generally how to compute the offset in each signal
- A table that shows the offset of `v1`, `v2`, and `i1`, respectively.
- Your COMMENTED Matlab code.

*Step 2 – Compute the RMS values:* Once the offset has been removed, determine the RMS value of the measured signals. To do this, use the actual definition of RMS, which for a general signal  $x(t)$  is:

$$X_{RMS} = \sqrt{\frac{1}{T} \int_0^T x^2(t) dt}$$

To compute the rms value in MATLAB, you may find the following tips helpful:

- Read the "Element-Wise Operations" section in the MATLAB guide. This will help to explain how to square all of the elements of a vector.
- To compute the integral, use the `trapz` command, which use the trapezoidal rule to compute the integral.
- Make sure to remove the offset from each set of measurements before making any computations.

- Note that you will need to compute the integral over one period, and thus you will need to examine the section entitled “Accessing Matrix Elements” and recall that a vector is simply a one-column or one-row matrix.

In your report, please provide the following:

- A detailed and well-explained analysis showing generally how to compute the rms value of each signal
- A table that shows the rms value of  $v_1$ ,  $v_2$ , and  $i_1$ , respectively.
- Your COMMENTED Matlab code.

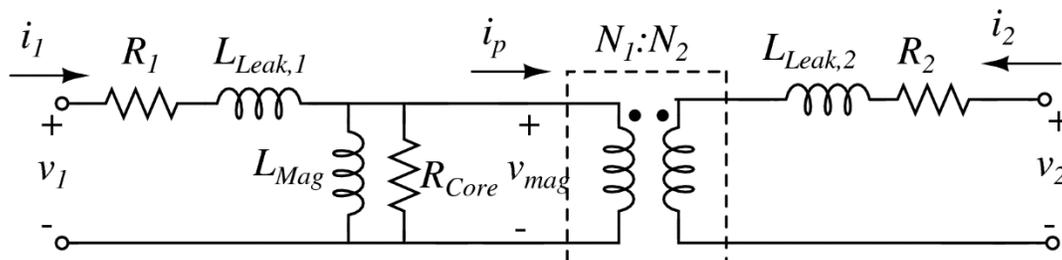
*Step 3 – Compute the conversion gains:* You now that the RMS values of the measurement signals. You must use these with the RMS values of the *actual waveforms* that you measured from the virtual instrument panel in the laboratory to determine the conversion gain for each of the sensors. As an example, I measured a true RMS value of 119.5V at the primary, and I measured the RMS value of the V1 sensor output to be 0.835. I then scaled all of my primary voltage measurements by  $119.5/0.835$  to determine the actual values.

In your report, please provide the following:

- A detailed and well-explained analysis showing generally how to compute the conversion gain of each signal
- A table that shows the rms value of the actual signals and the conversion factor for each sensor.
- Your COMMENTED Matlab code.

## Part 2: Determining the Turns Ratio

c) The model that we have used for the transformer in class is almost as shown below:



**In order to determine the parameters in the transformer model, we are going to begin by making the assumption that the magnetizing inductance and core-loss resistance are much, much larger than the leakage inductance and winding resistance.** We will later come back and justify this approximation.

In your report, use the assumption above to explain how our open-circuit tests can be used to determine the turns ratio. Justify using some analysis (i.e. equations) assuming that the leakage inductance is about 1% of the magnetizing inductance and that the winding resistance ( $R_1$ ) is about 1% of the core-loss resistance.

- d) Load the primary voltage and secondary voltage recorded during the open-circuit tests using the `csvread` command. Remove the offset and scale the data using the conversion factors that you determined previously.

In your report, please include the following:

- A properly labeled plot showing both voltages on the same axes. See the MATLAB Guide on the website for assistance in creating plots. Include your COMMENTED MATLAB code.
- Use the RMS quantities to determine the turns ratio. In reality, the primary has 1305 turns and the secondary has 746 turns. Since you are using only half of the primary, what should be the actual turns ratio? Compare this to your measurement. Why would there be any discrepancies? (Note that there really should not be much of a discrepancy).

### *Part 3: Determining the Magnetizing Inductance and Core-Loss Resistance*

- e) The primary voltage and current recorded during the open-circuit tests can be used to determine the magnetizing inductance. In your report, please provide the following:
- Assuming that the leakage inductance is about 1% of the magnetizing inductance and that the winding resistance ( $R_1$ ) is about 1% of the core-loss resistance, explain why you can neglect the voltage across the winding resistance and the leakage inductance. Use both math and words.
  - Draw a simplified circuit model under the assumption that you used in the first bullet.
  - You are given a measurement of the real power  $P$  flowing into the primary and the RMS value of the current and voltage at the primary when the secondary is open-circuited. Show how you can use these with the simplified circuit model to determine the core-loss resistance the magnetizing inductance. You must use both equations and words in your analysis. You will need these equations in the next part to determine the actual core-loss component and magnetizing inductance of our transformer.
- f) Now load the primary voltage and current recorded during the open-circuit tests using the `csvread` command as described above. Remove the offset and scale the data using the conversion factors that you determined previously. In your report please include the following:
- A carefully labeled plot showing the current and voltage on different axes. Use the subplot command as shown in the MATLAB guide so that you can see both the current and the voltage. It's difficult to use the same set of axes in this case since the voltage is so much bigger than the current.
- g) We need to compute the power flowing into the transformer when it was open-circuited. To do so, recall the definition of real or average power than we used in class:

$$P = \frac{1}{T} \int_0^T v(t)i(t) dt.$$

In your report, please include the following:

- Explanation of how you calculated  $P$
- COMMENTED Matlab code showing how you calculated the real or average power.
- Your calculated average power.

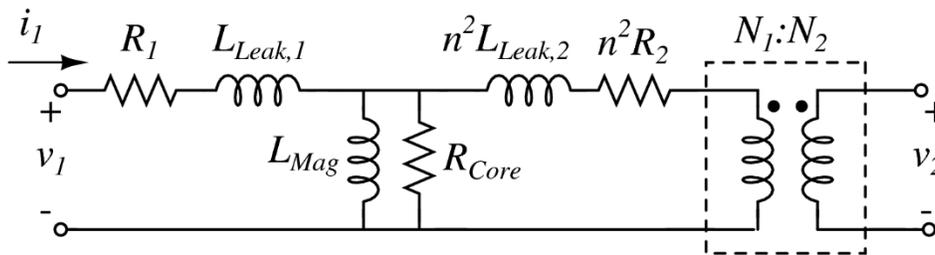
h) Using the  $P$  value from part g, your measured RMS values, and your equations from part e, determine the value of the magnetizing inductance and core-loss resistance. In your report, please include the following:

- A detailed and well-explained analysis that shows your calculations for the magnetizing inductance and core-loss resistance.
- A table showing your calculated magnetizing inductance and core-loss resistance.

As a hint, I found the magnetizing inductance to be somewhere between 1H and 10H.

*Part 4: Determining the Leakage Inductance and Winding Resistance.*

i) In power-system studies, the circuit model shown above is often manipulated somewhat. In your report, provide a detailed analysis showing that an equivalent version of the circuit model is the one shown below. In that figure,  $n = N_1/N_2$ . This model is commonly used in practice, and it is often called the T-model.



j) Now, let's once again assume that the impedance of the core-loss component and magnetizing inductance is so large that it can be neglected. Under this assumption, one can use the short-circuit measurements to determine the total winding resistance  $R_1 + n^2 R_2$  and the total leakage inductance  $L_{Leak,1} + n^2 L_{Leak,2}$ .

In your report, provide a detailed analysis that proves this. Assume that you are provided with a measurement of the average or real power  $P$  as well as measurements of the RMS voltage and current at the primary. Use both math and words.

k) Now load the primary voltage and current recorded during the short-circuit tests using the csvread command as described above. Remove the offset and scale the data using the conversion factors that you determined previously. In your report, please include the following:

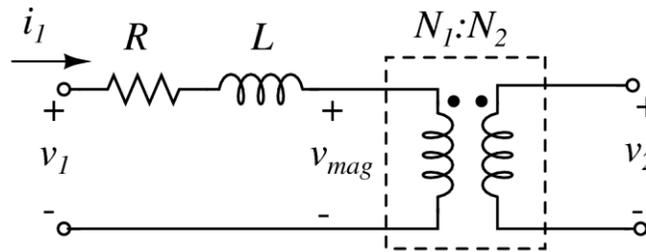
- A carefully labeled plot showing the current and voltage on different axes using the subplot command.
- A calculation of the average or real power  $P$ , including an explanation
- COMMENTED Matlab code showing how you calculated the real or average power.
- Your calculated average power.

l) Using the  $P$  value from part k, your measured RMS values, and your equations from part j, determine the value of the leakage inductance and winding resistance. In your report, please include the following:

- A detailed and well-explained analysis that shows your calculations for the leakage inductance and winding resistance.
- A table showing your calculated leakage inductance and winding resistance.

*Part 5: Using our parameters to analyze the transformer under load*

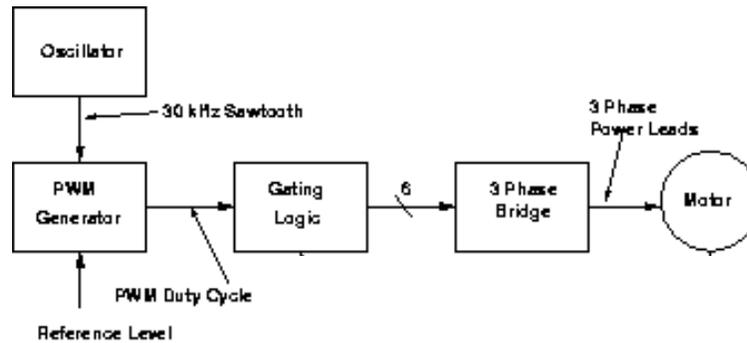
- m) Do your calculations justify our initial assumptions about the parameters? Explain. Briefly justify why the model shown below is often used in power system studies. Note that  $R = R_1 + n^2 R_2$  and  $L = L_{Leak,1} + n^2 L_{Leak,2}$ .



- n) Assume that a resistance  $R_L$  is placed on the secondary of the transformer model shown above. Show that the total impedance seen from the primary is  $Z = R + n^2 R_L + j\omega L$ .
- o) Now, load the primary voltage and current and secondary voltage and current recorded during the loaded tests using the csvread command as described above. Remove the offset and scale the data using the conversion factors that you determined previously. In your report, please include the following:
- A carefully labeled plot showing both the instantaneous primary-side power and the primary voltage on the same set of axes.
  - Compute the primary-side real power  $P$  using the measured primary voltage and current. Use this value to help explain the plot of the instantaneous power.
- p) Using the value of the real or average power  $P$  from part o and the measured RMS values of the voltage and current, determine the power factor and the angle between the voltage and the current. Include detailed analysis and explain all of your calculations.
- q) In part n, you found an expression for the total impedance of the transformer. Use this expression with the actual resistance and inductance values and the measured RMS value of the primary voltage to find the expected values for the following:
- Angle between the voltage and the current
  - Average Power
- In your report, please include the following:
- Detailed and explained calculations for the expected values of the angle and the average power
  - A comparison between your predicted power and the actual measured power. Note that your actual power should be about 5 or 6W higher than your predicted value and your angle should be really, really close to the actual. Explain any differences. As a hint, think back to the power that you measured during the open-circuit tests, and recall your assumptions.

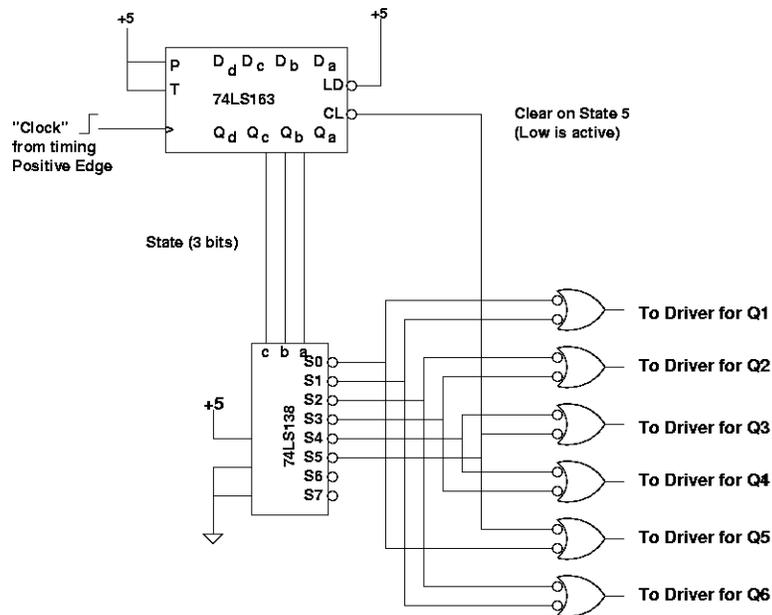
## Exercise 6: Constructing a Variable Speed Drive for an AC Motor

In this assignment, you will build the basic logic for an open-loop variable-speed drive (VSD) for an AC motor. The figure below shows a block diagram of the system. This approach is similar to what is found in many low-cost industrial drives. A more sophisticated system might also make use of closed-loop control, i.e. feedback. We're not ready for this.



### Part 1: Building the basic logic

In this exercise you must build the basic logic circuit that drives the three-phase inverter. The schematic is shown below:



Some important points to remember are the following:

- On the 138, the 3 enable pins must be connected like so:
  - G1: +5V
  - G2A: 0V
  - G2B: 0V

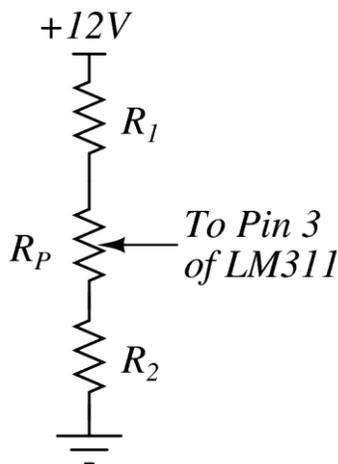
- The 6 negative-input OR gates must be created using 2 7400 ICs. You can also use 74LS00 ICs – The differences between the 7400 and the 74LS00 do not matter to us, so either chip will work.
- The clock should be provided by a function generator. Use the following settings:
  - Amplitude: 2.5V
  - Offset: 1.25V
  - Waveform: Square
  - Frequency: Between 200 and 400 Hz
- Power each of the ICs in this circuit using +5V, not +12V. This +5V can be obtained using one of the power supplies in the lab.

In your lab report, please answer the following:

1. What is the relationship between the frequency of the clock and the frequency of each of the 6 output signals?
2. If the 6 output signals were appropriately provided to the 6 MOSFETs in the inverter, what would be the relationship between the frequency of the clock and the frequency of the voltages produced by the inverter? In other words, what would be the relationship between the clock frequency and the frequency of the voltages applied to the motor?
3. On a set of vertically aligned axes, sketch each of the 6 outputs. Note that you won't be able to measure each of the 6 signals simultaneously, but you should be able to measure at least 2 of them simultaneously. Based on what we've seen in class, you should be able to complete the sketch.
4. Explain what it means for an output to be "active low."

### Part 2: Building a Pulse-Width Modulator

Use the same PWM modulator constructed previously with the LM311 and the 555 timer. Before doing so, replace your potentiometer at Pin 3 of the 311 with the following:

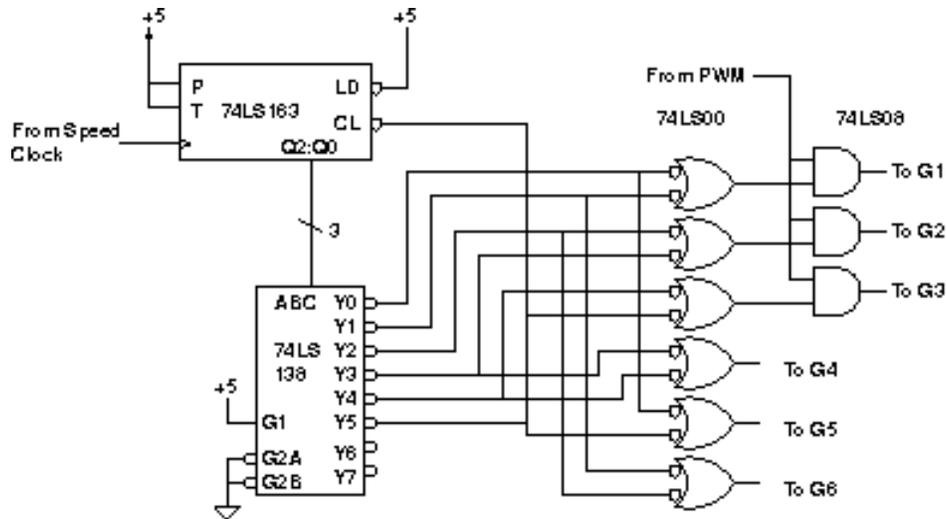


Choose the values of  $R_1$  and  $R_2$  so that the duty ratio of the LM311 output can vary from approximately 10% to 90%. To help you, consider the range of the signal applied at pin 2 of the LM311. That signal has a fixed lower limit and a fixed upper limit.

What you're doing here is choosing  $R_1$  and  $R_2$  so that voltage at Pin 3 of the LM311 can only travel within the same limits as the voltage at Pin 2.

### Part 3: Finishing the FSM

Once you've built the pulse-width modulator, modify your basic logic circuit from Part 1.. The schematic is shown below:



Some important notes about the final circuit:

- The PWM signal should be the output of your LM311.
- Don't modify any of the existing portions of the logic circuit.
- The output signals Q0, Q1, and Q2 on the 163 might be labeled as Qa, Qb, and Qc on your chip.

At this point, you are ready for check-off. Go to the AC motor test station in EPIC 2148. Connect the 6 output signals to the screw terminals at the test station as described below:

- |         |            |
|---------|------------|
| ○ +12V: | Terminal 1 |
| ○ GND:  | Terminal 2 |
| ○ G1:   | Terminal 3 |
| ○ G4:   | Terminal 4 |
| ○ G2:   | Terminal 5 |
| ○ G5:   | Terminal 6 |
| ○ G3:   | Terminal 7 |
| ○ G6:   | Terminal 8 |

Before powering anything up, please have a TA verify your setup.