

Chapter 4

Lab 3: Power Sources and Power Control

Objectives:

- Understand transistor operation
- Construct and understand common transistor devices:
 - Current regulator
 - Switch
 - Emitter follower
 - Push-pull follower
 - Darlington Pair
- Become familiar with DC motors
- Become familiar with AC motors and transformers
- Understand power rectification and DC power supplies

4.1 Introduction

In the last chapter we used operational amplifiers to build circuits that would amplify and integrate small signals. The operational amplifier is a very versatile electronic component, but its drawback is that it cannot supply a substantial amount of current – only about 10 mA or less in most cases. We could only drive the smallest and most efficient of motors with this current. This week we will solve the problem by taking a step backward technologically and introducing the transistor. Operational amplifiers, and most integrated circuits for that matter, are composed of many transistors fabricated on a silicon wafer. Their small size limits the current that can be safely provided; however, discrete transistors can be made much larger, and are therefore capable of handling more current and dissipating more heat. We will take advantage of such devices to amplify the current supplied by an op-amp. Finally, we'll shift our attention to DC power supplies. Using a transformer, we'll convert 115 VAC power from a wall plug to 12 VAC, then rectify the voltage using a diode bridge to produce an unregulated 12 VDC power source. Then the 7805 voltage regulator from Lab 1 will be added to make a 5 VDC regulated power supply.

4.2 Suggested Reading and Reference

Horowitz and Hill:

- Chapter 1: Foundations
 - 1.25 diodes
 - 1.26 rectification
 - 1.27 power supply filtering
- Chapter 2: Transistors
 - 2.01 basic transistor model (current amplifier)
 - 2.02 transistor switch
 - 2.03 emitter follower
 - 2.06 transistor current source
 - 2.16 Darlington connection
- Appendix F: Load Lines
- Appendix G: Transistor Saturation

Hayes and Horowitz:

- Chapter 2: Transistors (bipolar)
- Class 4: Transistors I: first model

4.3 Pre-lab Questions

1. Understanding the transistor. There is only a single pre-lab question for this lab. However, to answer it, you must first understand transistors. Be sure you understand the information in this section before coming to the lab (especially the summary in Table 4.3.1). To begin to understand the transistor, recall the diode - a device that we have now used many times. Although our experience has been limited to light emitting diodes (LED's), the behavior of standard diodes is qualitatively the same. If a voltage is applied in the reverse-biased direction, as Figure 4.3.1a demonstrates, there is no significant flow of current. If applied in the forward-biased direction, there is very little resistance to current flow as long as the applied voltage is greater than about 0.6V. For now, we will use the diode as a conceptual tool to understand the behavior of the transistor. Later, physical diodes will be used to rectify an AC power source.

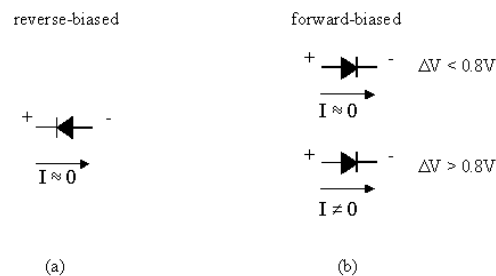


Figure 4.3.1: Summary of diode operation

The transistor is a three-terminal semiconductor device that come in two varieties. We call these two varieties npn and pnp. Table 4.3.1 summarizes the two types.

NPN type	schematic symbols	PNP type
	<p>looking into the terminals I_B = base current I_C = collector current</p>	
----- For Normal Operation: -----		
<ul style="list-style-type: none"> •Collector must be more positive than emitter. •Base-emitter diode is conducting and base-collector diode is reverse-biased. 		<ul style="list-style-type: none"> •Emitter must be more positive than collector. •Base-emitter diode is conducting and base-collector diode is reverse-biased.
----- If the Above are True then: -----		
$I_C = \beta I_B$ $V_B = V_E + 0.6V$	$(\beta \approx 100)$	$I_C = \beta I_B$ $V_B = V_E - 0.6V$

Table 4.3.1: A transistor summary

The three terminals are called the base, the collector, and the emitter – they are identified on the schematic symbols as well as on the transistor image in Table 4.3.1. If we were to put the probes of an ohm meter between the base and either the collector or the emitter of a transistor, we would think that the transistor is just a pair of diodes as illustrated in Table 4.3.1 (‘looking into the terminals’). For example, on an npn transistor, we could easily achieve current flow from base to emitter or base to collector by applying a voltage above 0.6V across these terminals. If we were to reverse the polarity, then no current would flow. However, there is more to a transistor than that. A current can flow from collector to emitter (npn) or from emitter to collector (pnp), but **only** if there is a base current (I_B). To achieve this, we must ensure that the conditions under the ‘For Normal Operation.’ heading are satisfied. Under these conditions, the collector current will be determined by the base current, or:

$$I_C = \beta I_B \quad \text{EQ 4.3.1}$$

Here, β is typically around 100, but is not constant. It can vary between different transistor models and is also affected by collector current (I_C), collector-to-emitter voltage (V_{CE}), and temperature. The collector and emitter currents differ by the amount of I_B ; however, Equation 4.3.1 shows that I_B is only about 1% of I_C so we usually assume that the collector and emitter currents are the same.

In the lab we will study the current amplification of the transistor by building the circuit shown in Figure 4.3.2. Build the circuit, and then follow through the below logic to understand how this circuit works:

1. The LabVIEW controlled Analog Out Channel 0 port applies a voltage across the collector and emitter (V_{CE}). If the current across the base-emitter is zero, then the current across the collector’s resistor (R_C) is zero (that is, no current flow through the transistor). LabVIEW automatically varies the Channel 0 voltage is from 0 to 10v.
2. The LabVIEW controlled Analog Out Channel 1 port applies a voltage across the base and emitter (V_{BE}). You, the operator, can vary this V_{BE} voltage, and then LabVIEW will automatically vary V_{CE} .
3. As the V_{CE} and V_{BE} voltage are varying, the Analog In Channel 1 observes and plots V_{CE} , and Analog In Channel 0 observes and plots V_{BE} as a function of collector current I_B . This allows you to witness the gain β as a function of V_{CE} and V_{BE} voltages. Remember that computers can only put out and take in voltages, but we want to observe currents. We therefore need to convert the voltages to current, which is why the resistor values must be known.
4. In your built circuit you can replace R_C with other resistors, and then change the value in the LabVIEW program, and then witness the gain β as a function of R_C .

Plotting I_C against V_{CE} in similar fashion to the I-V characteristics that were generated in Lab 2, produces an analysis called *load line*. Figure 4.3.3 contains a family of load lines for an ideal transistor. We will see that for low values of V_{CE} (less than about 0.2V), β drops rapidly. We call this regime *saturation*.

In Figure 4.3.3, the sloped line represents the response of the resistor. If we apply V_o to the top of the R_C in Figure 4.4.3, and there is no voltage drop across the transistor (that is, the transistor is theoretically shorted so $V_{CE} = 0$), then the collector current (I_C) – which is also the current through the resistor – is simply V_o/R_C . If V_{CE} increases to the level of V_o then there is no voltage drop across R_C and therefore no current. These points mark the extrema for I_C and V_{CE} . Real values will fall somewhere on the line in between. The horizontal lines in Figure 4.3.3 represent collector currents of ideal (i.e. $\beta=\text{constant}$) transistors for three different levels of base current. Because the resistor and transistor are in series, their currents must be the same, so in each case, the operating point (V_{CE} , I_C) is given by the intersection of the two lines.

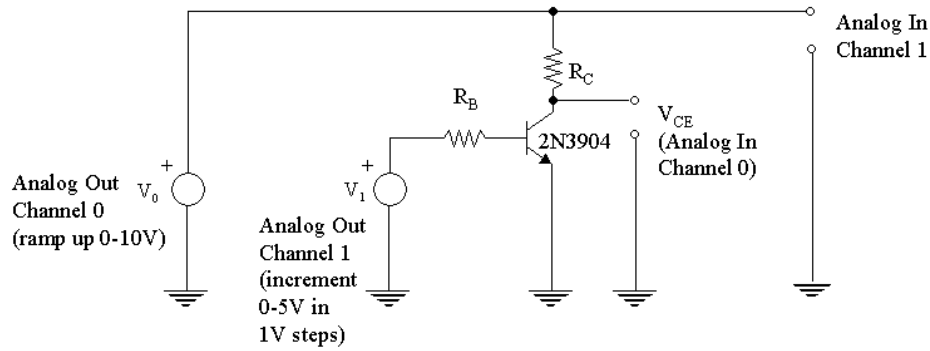


Figure 4.3.2: Load line circuit

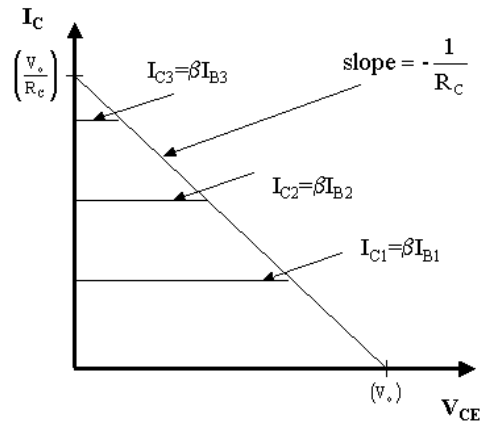


Figure 4.3.3: Load line analysis for an ideal transistor

Figure 4.3.4 is a schematic diagram of a simple current source constructed from a single pnp transistor. A current source is a device that supplies constant current, even with a varying load. Using the information for pnp transistors given in Table 4.3.1, and assuming an ideal transistor with $\beta=100$, select an R_B such that the current source in Figure 4.3.4 delivers a current of 10 mA. What is the maximum load for normal operation of the current source if the transistor saturates at $V_{CE}=0.25V$?

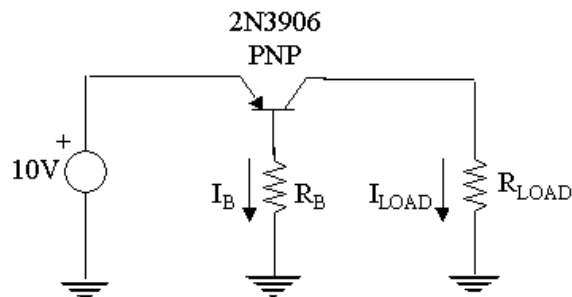


Figure 4.3.4: Transistor current source.

4.4 Laboratory Activities

4.4.1 The transistor.

In this lab session and in subsequent labs, you will be using four different transistors. They are given in Table 4.4.1.

Transistor type	Description
2N3904	NPN general purpose transistor
2N3906	PNP general purpose transistor
MJE3055T	NPN power transistor
MJE2955T	PNP power transistor

Table 4.4.1: Transistors in the MAE 221 Laboratory

The biggest difference between the general purpose and the power transistors is in the amount of current that they can handle. Before you continue, look at the data sheets for these transistors. They can be found in the ‘Lab Reference’ binder on your bench. Since you will be using these devices extensively, you should record some of its properties in your notebook. Pay particular attention to the maximum ratings (compare, in particular, the maximum collector currents I_C) and the gain β (also called h_{FE}). Also note the base, collector, and emitter terminals.

Obtain one of each transistor. You will need them during the course of this lab session. Select one and, with the Fluke meter on the diode setting, confirm that the transistor satisfies the diode illustration given in Table 4.3.1. If the positive probe is placed on the anode and the common probe is placed on the cathode, the meter should beep. If the polarity is reversed, the meter will not beep.

You are now ready to generate the load lines with the LabVIEW vi **Transistor.vi**. You must first build the circuit in Figure 4.3.2. Use 4.7k for R_B and 100 Ω for R_C . The **output channels should be amplified with the current amplifier in the breakout box**, connecting the power terminals to +15V, -15V, and ground on the GW power supply.

4.4.2 Regulating current with a transistor.

Begin by building the current source that you designed in the pre-lab question (Figure 4.3.4). Keeping in mind the maximum load that you calculated, choose three different resistors as loads, and determine the current supplied through each one by measuring the voltage across it with the oscilloscope. How much does the current vary between the three loads that you have chosen? How does this compare to the current through an ideal transistor? Was the initial estimate of β accurate?

Demonstrate your results to an instructor before continuing.

Such a current source could be used as a battery charger. As a safety feature, commercial chargers have an auto shut-off feature to prevent overcharging and explosion of the battery.

4.4.3 The transistor switch.

Because there can be no collector current if no base current is flowing, the transistor can be used as a switch. Its usefulness comes from the fact that the current gain β is very large so a small current applied to the base can switch a much larger current through the collector.

Begin by connecting an LED to a 10V power supply with a 100k series resistor, as shown in Figure 4.4.1. You should notice that the LED does not glow. What is the current through the LED?

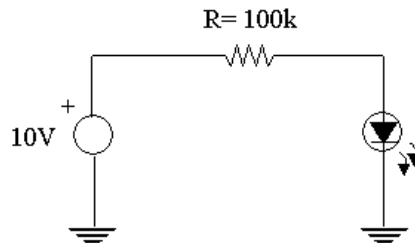


Figure 4.4.1: Low current into LED

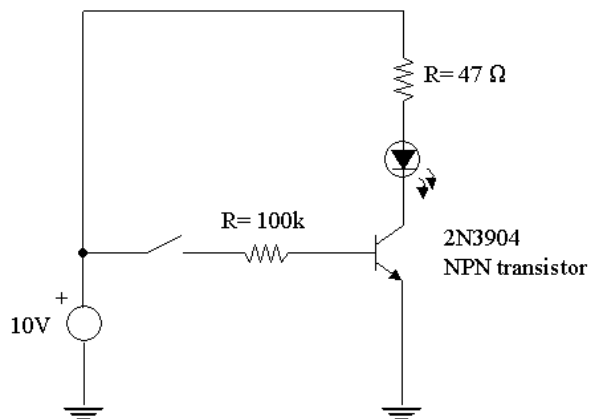


Figure 4.4.2: Current amplified through transistor switch

Now build the circuit shown in Figure 4.4.2. Rather than having the 100k resistor limit the current through the LED directly, it will limit the current through the base terminal of the transistor. Because I_C is much more than I_B (by a factor of β), the current is sufficient for LED illumination.

What are I_B and I_C ?

What is β ?

What is V_{CE} ?

Discuss these results with an instructor before you continue.

4.4.4 Amplifying current: driving a DC motor.

In the last lab we were able to drive a small motor using a differential amplifier. We used a pot to vary the voltage of one input while keeping the other constant, and thus controlled the speed and direction of the motor. This is because, without a load, the speed of a DC motor is proportional to the voltage applied across its terminals, and the direction of rotation is determined by the polarity of the applied voltage. We tried to drive another motor with the same circuit and saw that the op-amp could not provide sufficient current. We frequently encounter situations like this, and fortunately there are solutions. The following activities will introduce two transistor current amplifiers to solve this problem: the voltage follower and the push-pull follower.

Begin by building the op-amp circuit shown in Figure 4.4.3. The gain should be about 3. This is much simpler than the one we built in the previous lab (Figure 3.4.11) but the essential feature is the same: the op-amp is attempting to drive the motor. Use the motor-tach from the previous lab in this circuit, but before you connect it, ensure that the circuit is performing as expected by probing both the input and output of the linear amplifier with the oscilloscope. Use $\pm 15V$ for V_{CC} and V_{EE} , and use the function generator on your trainer to provide a sinusoidal input signal (6-10V peak-to-peak). Set the frequency to about 1 Hz. Since the input signal (and hence the amplified output signal) is oscillating between positive and negative voltages, we would expect the motor shaft to oscillate back and forth. Of course it doesn't because the op-amp cannot supply enough current for the motor to turn at all!

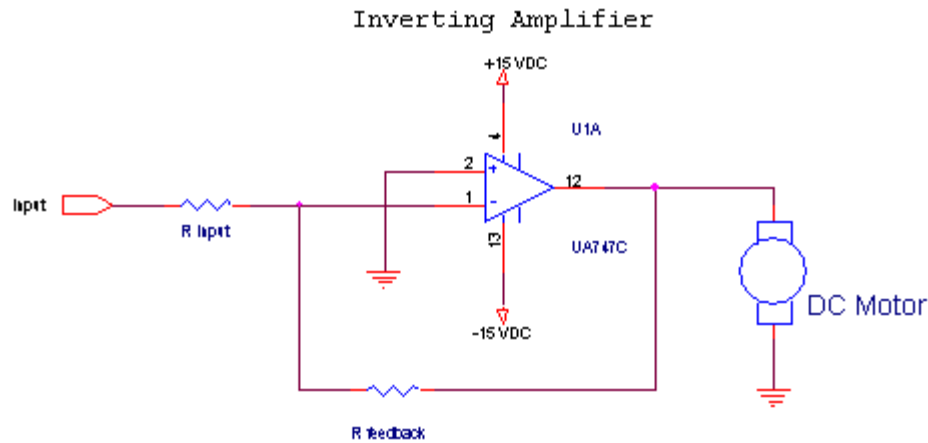


Figure 4.4.3: Initial motor driver configuration

In the previous exercise we used a transistor to amplify the current to an LED, so let's try this with a motor. Figure 4.4.4 shows a the base of an npn transistor connected to the output of the op-amp. Recall that for an npn transistor under normal operating conditions, $V_E = V_B - 0.6V$ we therefore call this an **emitter follower**. Build this circuit using about 3k for R_{output} and observe the result. You should notice that the motor is turning, but only in one direction. This is because an npn transistor can only *sink* collector current so there will only be an output when V_B is greater than about 0.6V.

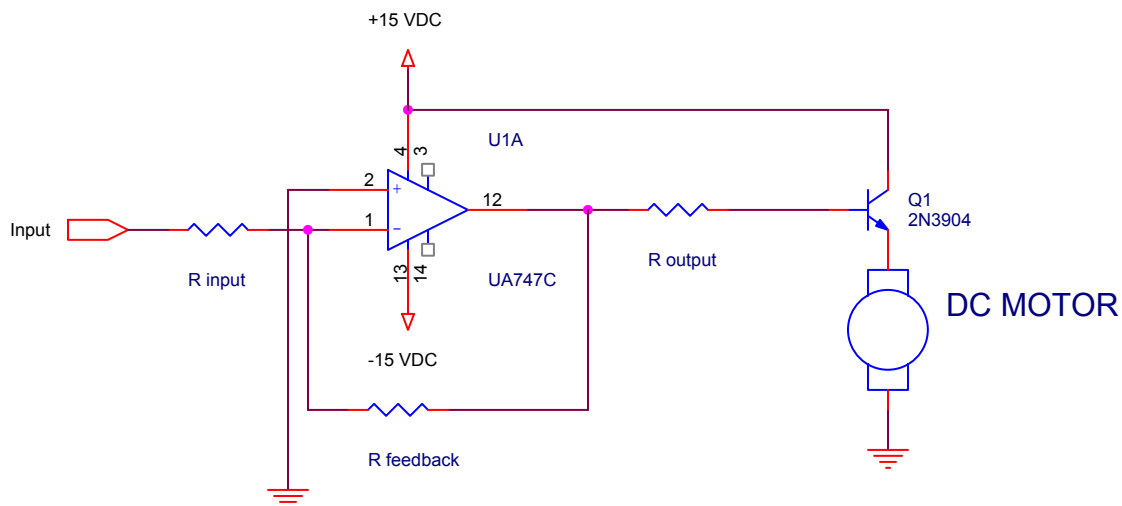


Figure 4.4.4: Unidirectional current amplification with an emitter follower

Well, at least the motor turns. However, we want the motor to turn in both directions with alternating signs of the input signal. To do this, we need to add a pnp follower to handle the negative voltage swings. This produces a **push-pull follower**. Figure 4.4.5 shows the circuit with the push-pull follower. Before you run the motor, use only a 1k resistor as the load and look at the output voltage level of the push-pull with your oscilloscope. There is a problem! The output does not faithfully reproduce the input. Whenever the input signal is between $-0.6V$ and $0.6V$, the output is zero because of the diode behavior of the base-emitter connection. This is called *crossover distortion*. In the motor, it can introduce vibrations. The vibrations will be somewhat damped by the inertia of the motor and may not be a problem. However, if the push-pull was being used to amplify an audio signal, and a speaker was being driven, the sound would be terrible. Audio amplifier manufacturers have many tricks for removing crossover distortion to produce high-quality sound. We will look at one simple technique that will be sufficient for our motor driver circuit.

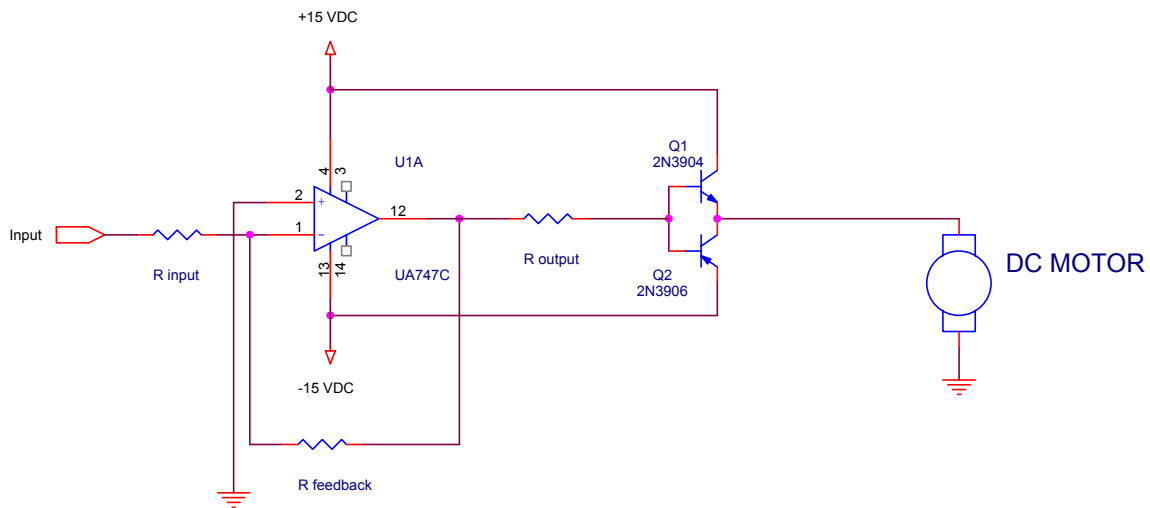


Figure 4.4.5: Amplifying current using a push-pull follower

To remove crossover distortion, consider the linear amplifier. The feedback loop ensures that the output of the op-amp is proportional to the input signal. If we include the push-pull follower inside the feedback loop, as Figure 4.4.6 shows, then the op-amp will try to make the output of the push-pull proportional to the input signal produced by the function generator. To see how it does this, again replace the motor with a 1k resistor. Using the oscilloscope channels, compare the output of the push-pull to the signal generated by the function generator. Note any distortion you see in the push-pull output signal. Now look at the output of the op-amp. This should look very distorted. Clearly the op-amp is working very hard to keep the output of the push-pull smooth. Now replace the resistor with the motor and note any improvements that you see.

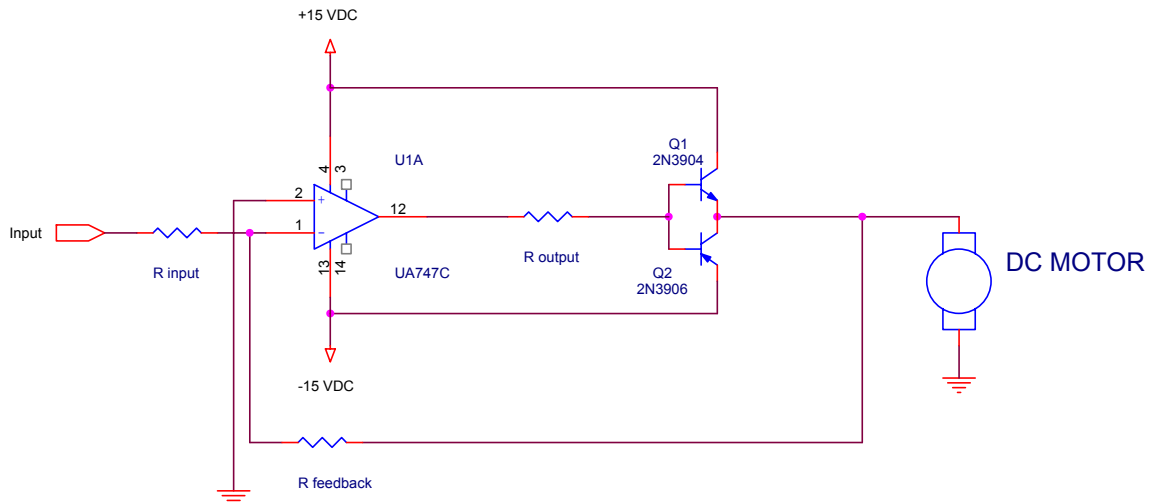


Figure 4.4.6: Removing crossover distortion with feedback

Demonstrate your motor driver to an instructor.

Keep this circuit assembled for the next activity.

4.4.5 Speed control on a 115V synchronous motor.

The rotational speed of an AC synchronous motor is proportional to the frequency of the AC voltage that drives it. Therefore, if a synchronous motor is run from the 60 Hz power of a wall outlet, it will have only a single speed (and direction). An example of such a device is the lab timer on your bench. Plug it into one of the 115 VAC outlets on your bench, and run it.

If we could produce a variable frequency power source for this timer, we could then modify its speed. We will do just that.

In the previous exercise, you built a circuit that will provide the basis for our speed controller. We will adjust the motor speed by changing the function generator frequency. The problem is that the timer requires 115 VAC, whereas we only have around 5 VAC coming out of the push-pull. The solution is to *step up* the voltage through the use of a transformer. A transformer consists of a primary coil and a secondary coil that are inductively connected by an iron core. An excitation current in the primary coil induces changing magnetic fields in the core, which induce currents in the secondary coil. The ratio of the input and output voltages is proportional to the ratio of the number of turns in the primary and secondary coils.

Remove the motor from your circuit. By looking at the signal with your oscilloscope, adjust the function generator to 60 Hz. **Turn off the function generator and power supply.** Connect the output of your push-pull to the primary coil of the transformer. The output coil (connected to the *wall plug* style outlet) will be at approximately 115 VAC when power is supplied.

Caution! Do not touch any objects exposed to 115 VAC. You will receive a shock that can be harmful or fatal. The following activity should only be conducted during the normal lab period, or when an instructor is present.

You must make sure that the circuit is working properly by measuring the output voltage of the transformer. Use caution when executing this procedure.

Begin by making sure the switch on the transformer box is in the OFF position. Also, confirm that the power supply and function generator are off so that there is no current entering the primary windings of the transformer. Insert the provided plug stub into the output socket, and connect the oscilloscope probe across its terminals, ensuring that the ground wire on the probe is connected to the *neutral* terminal, and that the probe and oscilloscope channel are both set to 10X. **Do not ever touch the exposed terminals while the plug is inserted into the socket and the power is on (this is the dangerous part).** Turn on the power supply and function generator to provide an input signal to the transformer. Then, turn on the transformer switch to supply power to the output socket. You should see the voltage trace on the oscilloscope screen. We require a root mean square voltage of 115V, which means that the peak voltage should be about 160V (or 320V peak-to-peak). To obtain the right voltage level, you must adjust the amplitude on the function generator because the voltage gain of your circuit is fixed. When you have achieved the right voltage, turn off the switch on the transformer box and turn off the function generator and power supply, then remove the plug from the socket.

The output voltage level and frequency are now correct and we are ready to run the timer. Turn on the power supply and function generator and plug the timer into the socket on the transformer box. What happens? Is there any noise? Is there any motion? Probably not much because our amplifier circuit is not producing enough current to drive the timer. We must therefore boost the current even further. This can be done by creating a **Darlington pair** on each leg of the push-pull follower. To create a Darlington pair, we connect the emitter of each transistor to the base of another transistor as shown in Figure 4.4.7. This results in a much greater output current. If the emitter current of the original transistor is $I_{E1} = \beta_1 I_{B1}$, then the emitter current of the second transistor is $I_{E2} = \beta_2 I_{B2} = \beta_2 I_{E1} = \beta_2 \beta_1 I_{B1}$. In order to provide that amount of current though, we need much larger capacity transistors so the added transistors should be power transistors – the MJE3055 NPN, and MJE 2955 PNP. Add the power transistors to your circuit to create the Darlington pairs, and the circuit will be complete. Turn on the

power supply and function generator and observe the clock again. Adjust the output frequency of the function generator and watch as the speed of the timer changes. What happens if the speed is too high or too low? Can you explain the phenomena that you observe?

Demonstrate your motor speed controller to an instructor.

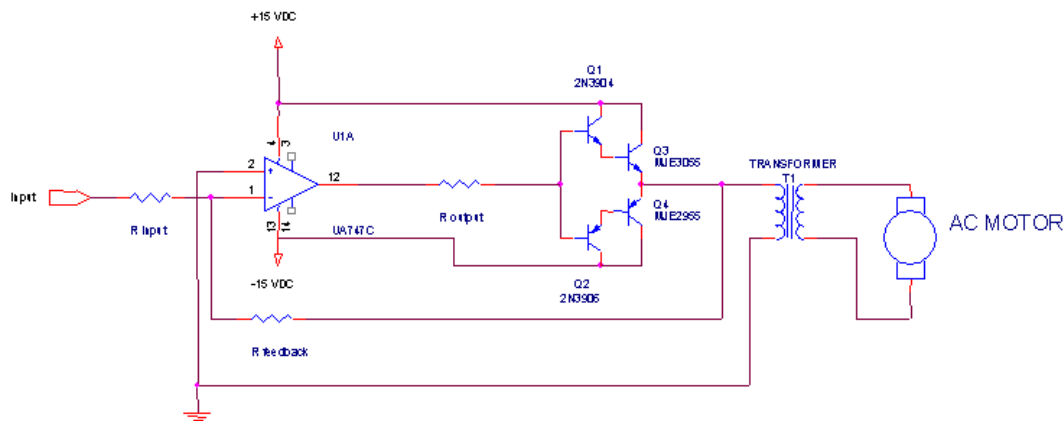


Figure 4.4.7: Darlington pair current amplifier

4.4.6 Construction of a DC power supply

In this exercise we will construct a 5 VDC power supply similar to the one in your trainer. Effectively, we are achieving the opposite goal that we did in the previous two sections because we are starting with a 115 VAC source and creating a 5 VDC source.

Step 1: reduction of AC voltage. The 115 VAC signal is reduced to 12 VAC using a step down transformer. This is like the transformer that we used for the AC motor controller, except that we excite the high voltage side with 115 VAC current. The output of this transformer will be 12 VAC.

Step 2: rectification of the AC source. The AC source produces alternating positive and negative voltage. We only want the positive so we must take the negative swings and turn them around. To do this, we make use of a bridge rectifier. The diamond-shaped circuit element in Figure 4.4.8 is what we call a **bridge**. A full bridge has four terminals: two inputs and two outputs. We have a diode in each arm of the bridge, which allows current flow in only one direction. This configuration takes an AC current across the inputs and produces a rectified signal across the outputs.

Build the circuit shown in Figure 4.4.8, using a 1k resistor as the load. Look at the voltage across the resistor with your oscilloscope.

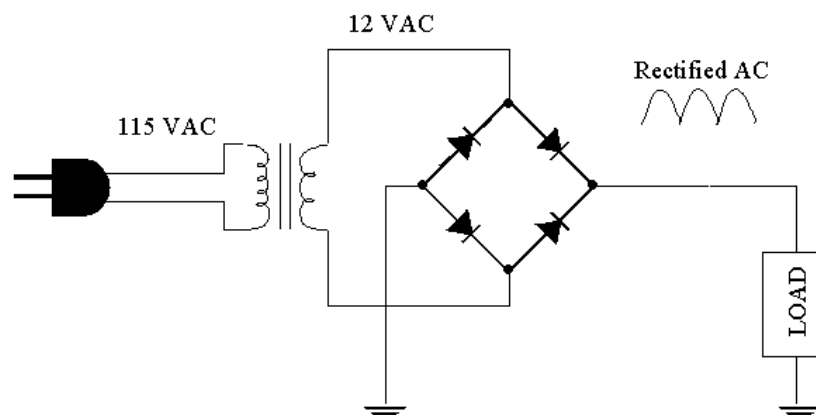


Figure 4.4.8: 12V rectified source

Step 3: filtering. We have a very poor DC power source because the voltage fluctuations are huge. We need to reduce these fluctuations by adding a capacitor to the output, as Figure 4.4.9 shows. Try adding a capacitor on the order of $10\ \mu\text{F}$, and see how that changes the output. Double the capacitance and note differences in the *ripple*. Each time the bridge voltage rises, the capacitor is charged. When the bridge voltage falls, the capacitor discharges, delivering current to the load and thus compensates for the lack of bridge current. The larger the capacitor, the more smoothing.

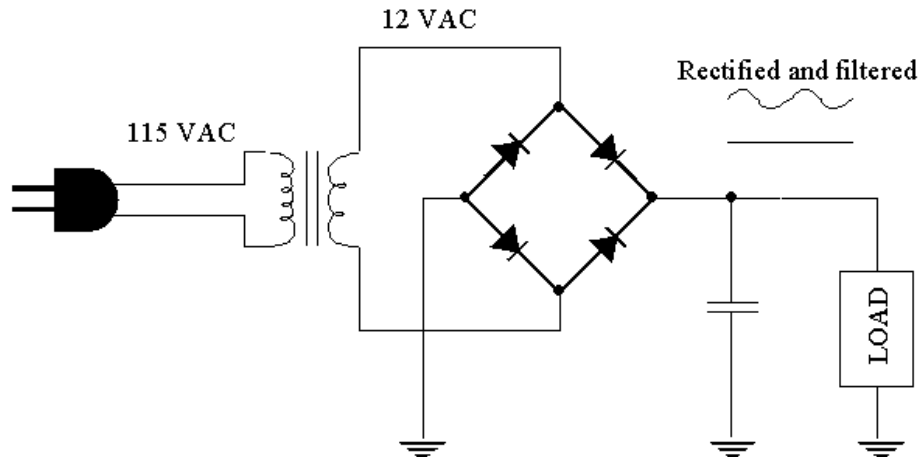


Figure 4.4.9: Filtering the voltage source

Step 4: increased loading. Replace the 1k resistor load with a DC motor. Continue monitoring the voltage level with the oscilloscope as you run the motor. Because the impedance of the motor is much lower, it draws much more current, thereby increasing the ripple of our power supply. To improve this, we must increase the capacitance in parallel with the load. Replace your capacitor with one on the order of $100\mu\text{F}$ and note the difference.

Step 5: regulating the power supply. You may have noticed that the voltage level drops with increased current drawn by the load. This makes a poor voltage source. To improve this, we will regulate the output voltage at 5V , using the 7805 voltage regulator that was used in Lab 1. The final circuit is shown in Figure 4.4.10. Build this circuit and run the motor, again observing the voltage across the motor with your oscilloscope.

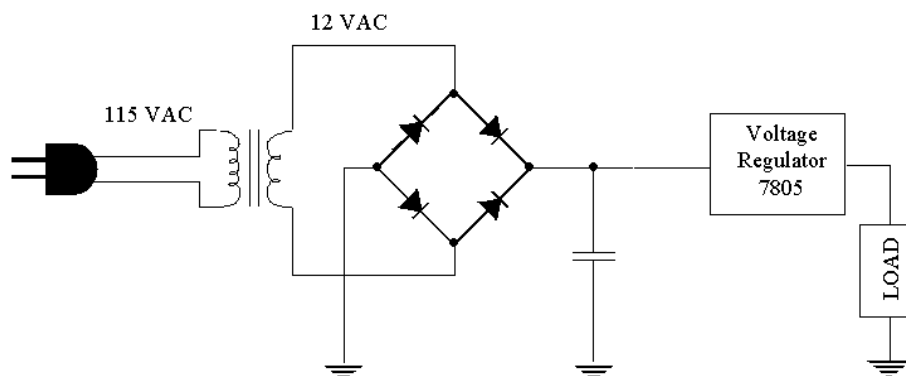


Figure 4.4.10: Regulated 5VDC Power Supply

Demonstrate your regulated power supply to an instructor.

4.4.7 Clean Up

Again, before leaving, make sure that all tools and components are put in their proper places and lab instruments are turned off. Do not put broken components back in their containers – throw them out. Remove your pinboard from the trainer, label it with your name(s) and store it in the cabinet at the side of the lab.

4.4.8 Generation of the technical reference sheet

Generate a technical reference sheet for the transistor. Be sure to include all of the transistor devices that you have built in this lab.