EE320L Electronics I

Laboratory

Laboratory Exercise #4

Diode Rectifiers and Power Supply Circuits

By

Angsuman Roy

Department of Electrical and Computer Engineering

University of Nevada, Las Vegas

Objective:

The purpose of this lab is to understand how to design and build simple power supply topologies.

Equipment Used:

- Transformer (ideally center-tapped)
- Oscilloscope
- Breadboard
- Jumper Wires
- Resistors, Capacitors
- Rectifier Diodes (1N400X where X is 1, 2, 3 etc.)
- Linear Regulators (MC7805, MC7905)
- LEDs

Background:

At any given moment, a person is probably surrounded by a dozen or more power supply circuits. Even if one is outdoors, the cell phone in their pocket contains numerous power supply circuits. Fundamentally a power supply converts one type of electrical power into another form of electrical power. The biggest example of this is converting the household AC power into the DC power that is needed by most electronics. Another example of this is converting one DC voltage into another DC voltage. An entire branch of electronics known as DC to DC converters is devoted to this. Regardless of the type of power conversion, energy must be conserved and there is always a loss of energy in the form of heat in the power conversion process. Power supply circuits can be grouped into two main categories, linear and switching. Currently, the vast majority of power supplies are of the switching variety (mainly DC-DC converters) due to their high efficiency and low cost. This lab will focus on linear supplies which are easy to understand and provide a good foundation for beginners.

The focus of this lab is on converting AC to DC (rectification), filtering, and regulation. A basic block diagram of a linear power supply circuit is shown below in Fig. 1. The three main components are the transformer, rectifier and filter. The transformer converts one AC voltage into different AC voltage in this case 120V to 12.6V. The rectifier converts AC to DC and can be implemented in many ways. The filter smooths the DC so that it is steady for powering a load. The output voltage given as 17.8V assumes no regulation and perfect rectifier components so there is no voltage loss.

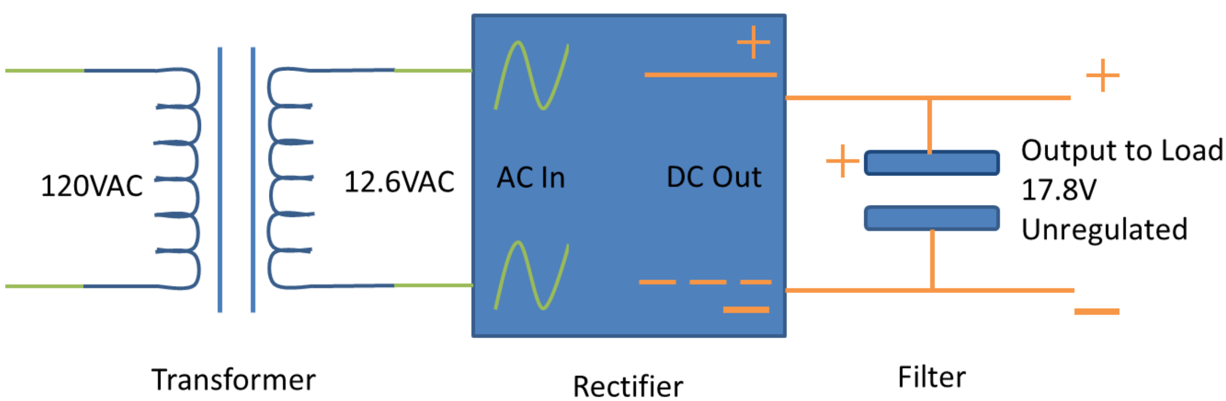

Figure 1. Basic linear power supply block diagram.

Transformers:

The transformer is an amazingly elegant component. At its simplest, it is just two coils of wire that are separated by some distance and insulated from each other. In some cases there is a material in between the two coils that changes properties of the transformer. Despite this, the electromagnetic properties of transformers make their design into its own career. For our purposes we just need one simple formula. This formula is shown below in Fig. 2. The two sides of the transformer are the primary and the secondary. Which side is which is determined by the manufacturer and application. For example, a particular transformer could have a primary of 120V and a secondary of 10V. To implement this, the turns ratio $\frac{N_s}{N_p}$ would have to equal $\frac{10}{120}$ or 0.083. The secondary could have 100 turns and the primary could have 1200 turns and that would satisfy this ratio. Since we are not actually building transformers we don't know what the actual number of turns is nor do we need to know. However, we do know what the ratio between the primary and secondary is since those voltages should be marked on the transformer.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \text{N} = \text{Turns Ratio}$$

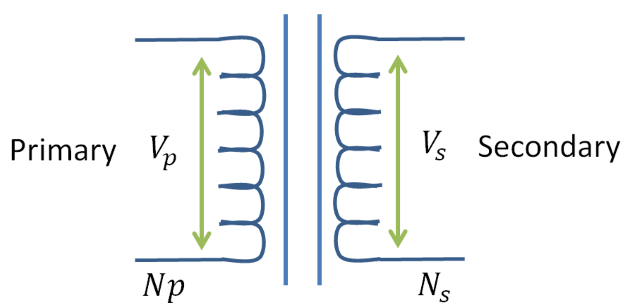

Figure 2. Transformer schematic symbol and parameters.

Next, it is important to know the VA rating of the transformer and the current rating. The VA (volt-ampere) is a unit of complex power. The watt (W) is a unit of real power. In DC circuits all powers are in the form of watts. However, in AC circuits, voltage and current can be generated in a way which performs no work at all due to their phase relationship. To account for this, transformers are rated in VA which is the product of a transformer's rated voltage and rated current. The real and imaginary powers within circuits is outside the scope of this lab and we will make the approximation that one volt-ampere is equal to one watt. This assumption is fine if most of the circuit elements are linear and there are no switching power supplies. It is good practice to use a slightly larger transformer than required for safety purposes. For example, if we would like to design a power supply for a 10W circuit we would use a VA rating that is a little larger such as 12VA.

All the current and voltage relationships in the transformer are shown below in Fig. 3. If at least two variables from one side and one variable from the other side are known then it is possible to calculate the missing quantities. For example if a transformer is marked 120 VAC 1A on the primary side and 12 V on the secondary side, it is simple to calculate that the secondary current is 10 A, the turns ratio is 10, and the VA rating is 120 VA.

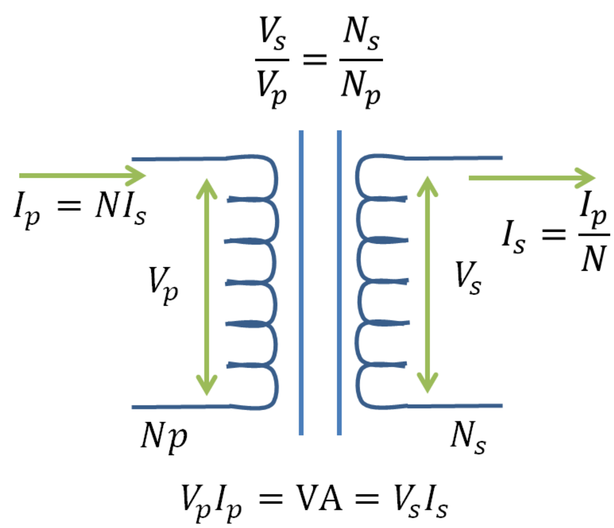

Figure 3. Current, voltage and VA relationships in a transformer.

Rectifiers:

The rectifier is a circuit that converts AC into DC. The first rectifiers were made from vacuum tube diodes. As with most things, solid state diodes have replaced them in this application. A diode is an electronic component which allows current to only flow in one direction. That is, current only flows when the voltage applied to the anode terminal of the diode is more positive than the cathode terminal. This is illustrated in Fig. 4. Current only flows through the diode during positive portions of the AC waveform. This illustration assumes a return path to ground through a load but it has been omitted for clarity. A single diode forms the basis for a **half-wave rectifier**.

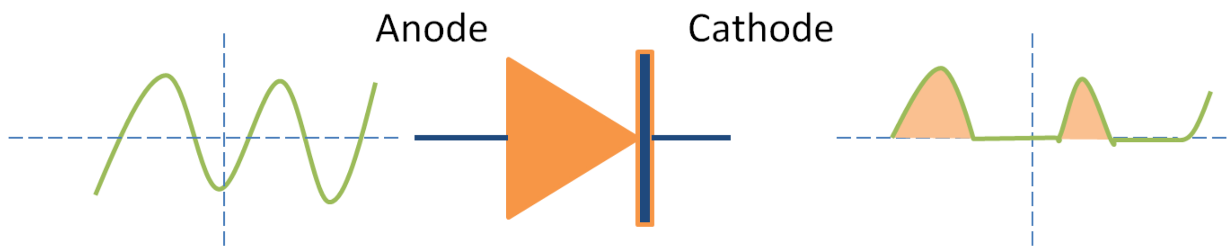

Figure 4. Diode operation.

A linear power supply based on a half-wave rectifier is shown in Fig. 5. The waveform at each point in the circuit is shown. However note that the “Rough DC” and “Smooth DC” is actually the same node. Both were included to show how the filter capacitor smooths the DC into a flat line. This is only true when there is no load. When the power supply is providing power to a load, a ripple voltage occurs. This is shown in Fig. 6. The waveforms are color coded and match the colored arrows on the schematic. The AC voltage is in green and has an amplitude of 17 V peak. The diode current is in black. Notice that the diode current only flows when the AC waveform is above 0.6V (the forward voltage of the diode). Further, notice that the current stops flowing once the DC level (blue) is charged to the peak value of the AC. When the AC waveform drops below 0.6V, the diode current stops and the capacitor is getting discharged by the load resistor. The process repeats once the AC waveform is up to 0.6V. This “saw tooth” shaped wave is known as ripple.

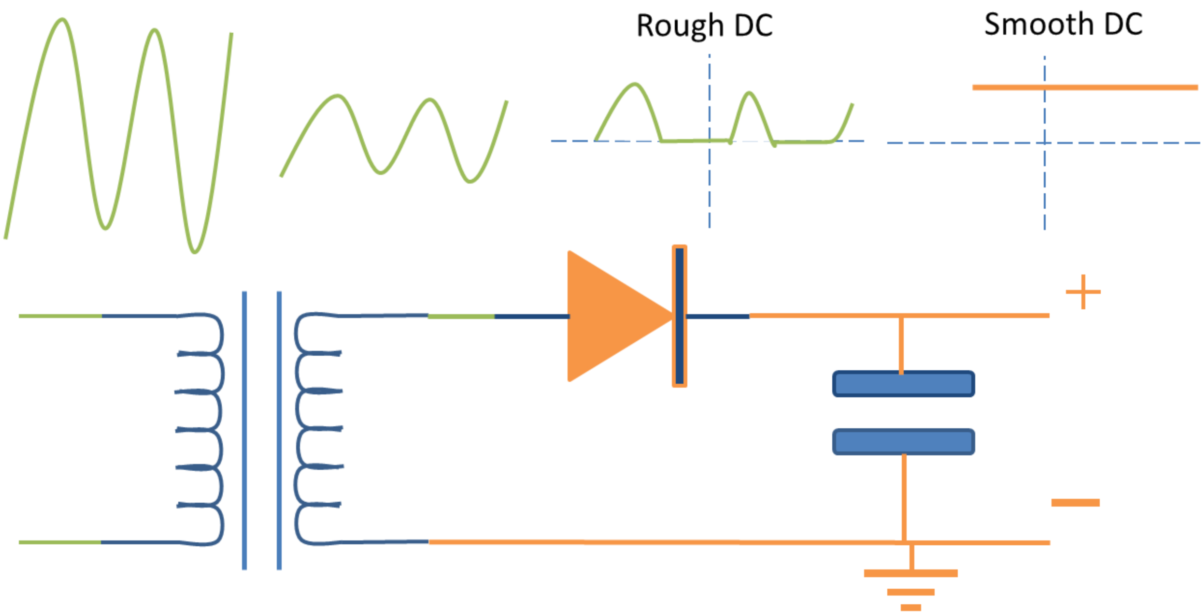

Figure 5. Half-wave rectifier.

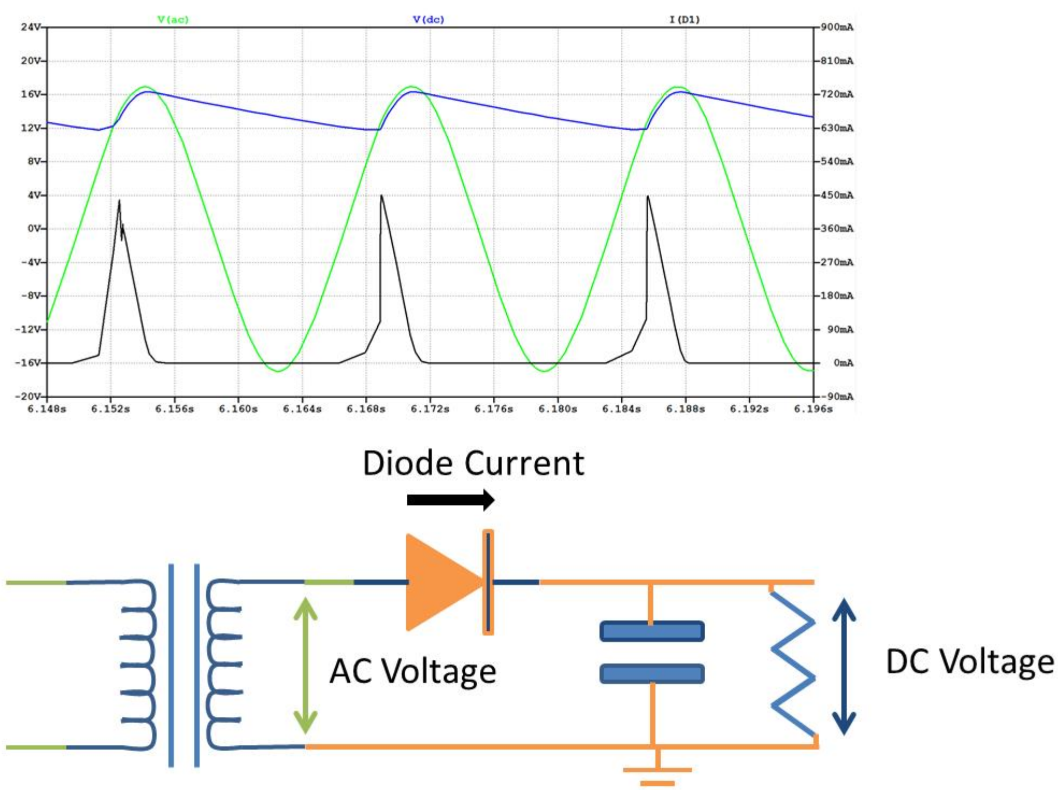

Figure 6. Half-wave rectifier showing relationship between voltages and diode current.

The biggest disadvantage of the half-wave rectifier is that the negative portion of the AC voltage isn’t converted to DC. In a way, half the potential of the power supply is being thrown away. The solution to this circuit is the bridge rectifier. The schematic of the bridge rectifier is shown below in Fig. 7. The bridge rectifier is made up of four diodes arranged in a ring. An easy way to remember how to draw it is to think of two sets of series diodes that are back to back. An easy way to remember how to wire up the bridge rectifier is as follows. AC is both positive and negative, so the points where the diodes’ anode and cathode meet are where the AC input is applied. For DC, think opposites. The positive DC terminal is where two cathodes meet while the negative DC terminal is where two anodes meet.

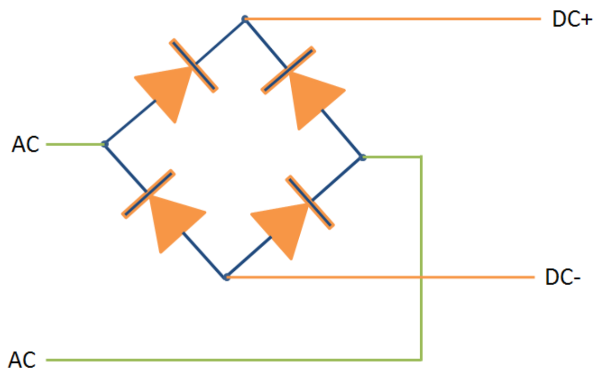

Figure 7. Bridge rectifier schematic.

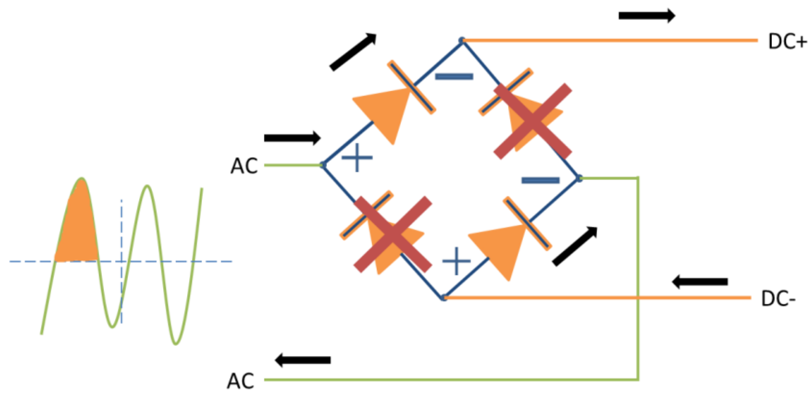

Figure 8. Bridge rectifier operation during positive AC portion.

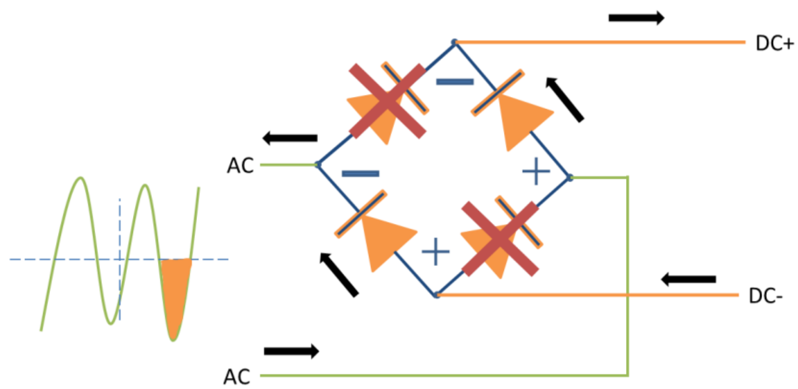

Figure 9. Bridge rectifier operation during negative AC portion.

Next, let's examine how the bridge rectifier functions. Fig. 7 and Fig. 8 show how the diode currents flow depends on the polarity of the AC waveform with respect to the DC side. There is a lot going on in these figures and it is important to carefully follow the paths. The black arrows represent the current flow through the diodes; the red "X's" mean that those diodes are not doing anything; and the blue "+" and "-" indicate the relative voltage across the diode. During the positive portion of the AC waveform, the anode side of the top-left diode is higher in voltage than the cathode side which results in current flow. The anode side of the bottom-right diode is at a higher voltage than the cathode side which results in current flow back to the AC source. During the negative portion of the AC waveform, the cathodes of the top right and bottom left diodes are more negative and therefore turned on. The current paths are as indicated in Fig. 9.

Let's put everything together into a basic unregulated power supply. The power supply in Fig. 10 has a bridge rectifier, transformer and filter capacitor. The load resistor is used to model whatever the load is that is connected to the power supply. The rectified DC value is the peak value of the AC voltage from the transformer minus two diode drops. This is because there are two diodes in total between the return path to the transformer.

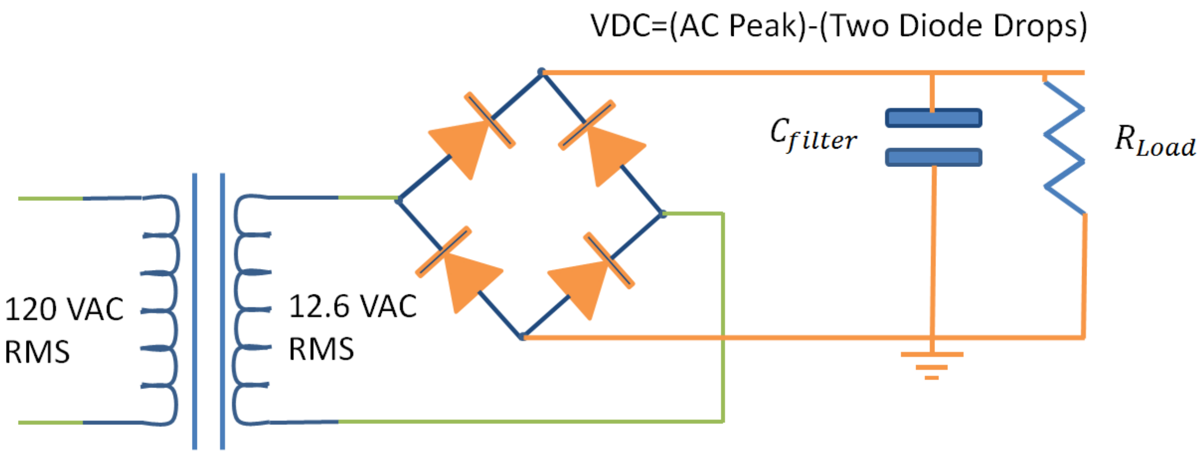

Figure 10. Simple power supply with bridge rectifier.

The schematic used to simulate a power supply like this is shown in Fig. 11. The bridge rectifier is drawn a bit differently but it is the same circuit as shown above in Fig. 10. With the 100 microfarad filter capacitor there is a significant amount of ripple voltage as shown in Fig. 12. Notice how the peaks of the rectified DC do not match the peaks of the AC due to the diode drops. Also note that the frequency of the ripple is 120 Hz which is double the AC frequency. This is an advantage over the half wave rectifier (60 Hz ripple) because smaller capacitors can be used to filter the ripple.

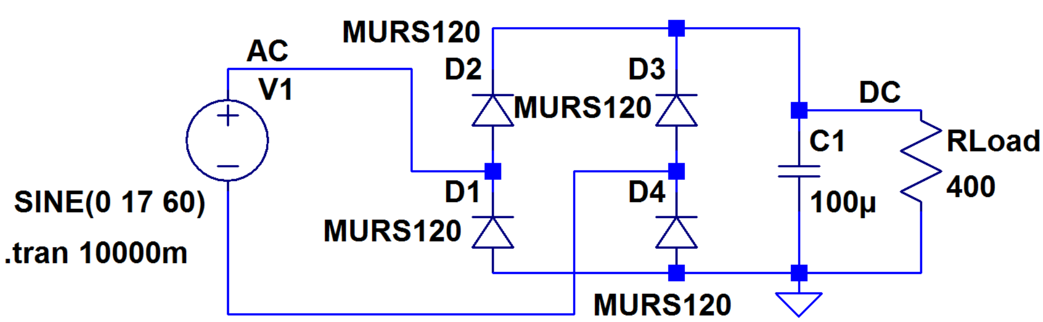

Figure 11. Simulating the bridge rectifier.

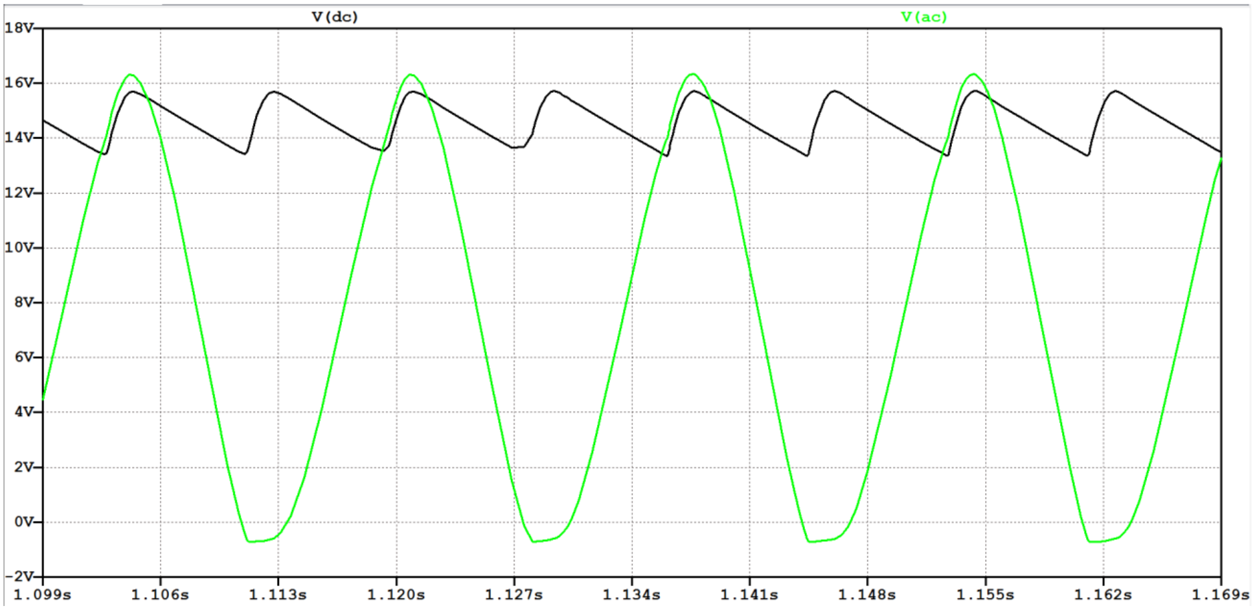

Figure 12. DC output with ripple voltage.

The equation for calculating the ripple voltage of a bridge rectifier is given by,

$$V_{p-p\ Ripple} = \frac{I_{Load}}{2 f_{AC} C_{Filter}}$$

Where ILoad is the load current, f is the frequency of the AC from the transformer and CFilter is the value of the filter capacitor. Make sure to use the actual AC line frequency (60 Hz) and not the frequency of the ripple itself. The 2 accounts for the fact that the ripple is at double the frequency. This equation is used as a starting point for sizing the filter capacitor. Generally, a power supply engineer will be given a maximum ripple value to design around. It's best to do one calculation to size the filter capacitor and then simulate the design to fine tune it and account for other factors that may be hard to calculate.

The bridge rectifier can be used with a center-tapped transformer to create a dual supply with positive and negative outputs. This is displayed in Fig. 13. A center-tapped transformer has a connection made to the middle of the secondary coil. This allows for two phases of AC that are 180 degrees apart if the center tap is grounded. The outputs from the bridge rectifier become the positive and negative DC voltages. Two filter capacitors are connected in series between the positive and negative rails with the middle connection grounded. The bleeder capacitors serve two purposes. The first purpose is to discharge the capacitors relatively quickly after power is turned off so that the user does not get shocked by assuming that the capacitors are already discharged. A desired discharge time can easily be calculated using the RC time constant. The trade-off is that during normal operation the bleeder capacitors are part of the load and do consume some current. Generally values between 10k and 1 MEG are used depending on the application. The second purpose of a bleeder capacitor is for balancing. The series filter capacitors function as a capacitive voltage divider. If they are not closely matched then one capacitor will have a higher current flow through it than the other one. This can cause the capacitor to heat up and fail prematurely. The bleeder resistor helps balance the loads if lower valued resistors are used. There are equations for calculating this but it is outside the scope of this lab. The load resistors have been omitted for clarity from Fig. 13. The loads can be connected either between V+ and V- or between either rail and ground.

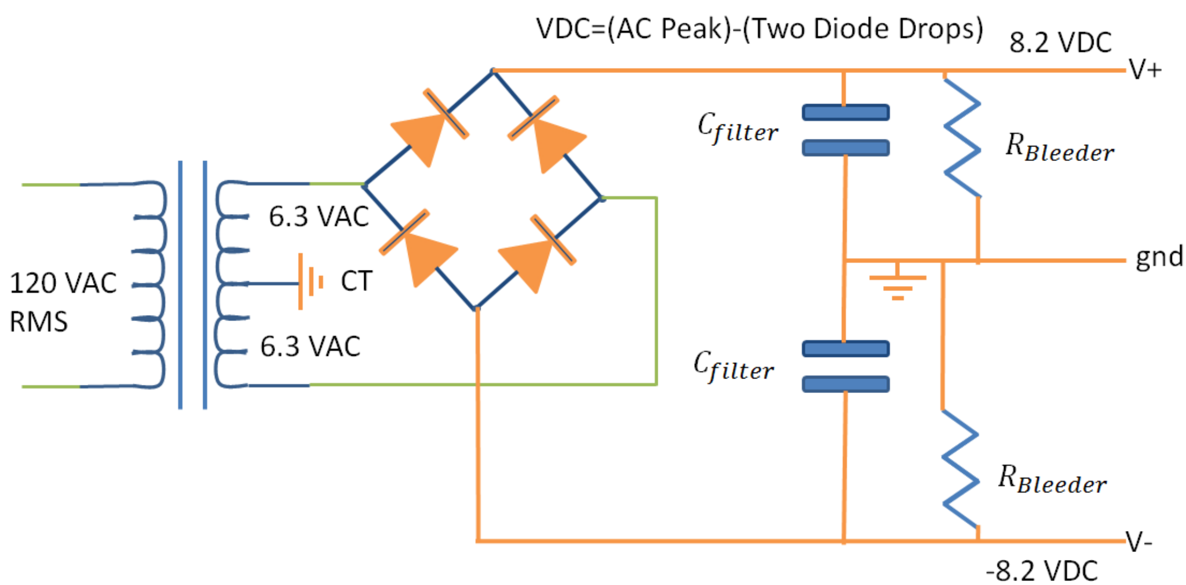

Figure 13. Schematic of dual supply.

The schematic in Fig. 14 can be used for simulating this circuit. Two AC sources are used to model the center-tapped transformer. The simulation results are shown in Fig. 15. The two positive and negative DC outputs are shown as are the two AC phases. Since AC has both positive and negative portions, referring to an AC source as “negative” generally means that it is 180 degrees out of phase of another AC source. In this case our 12.6 VAC RMS transformer has been split into “positive” and “negative” AC sources with 6.3 VAC RMS.

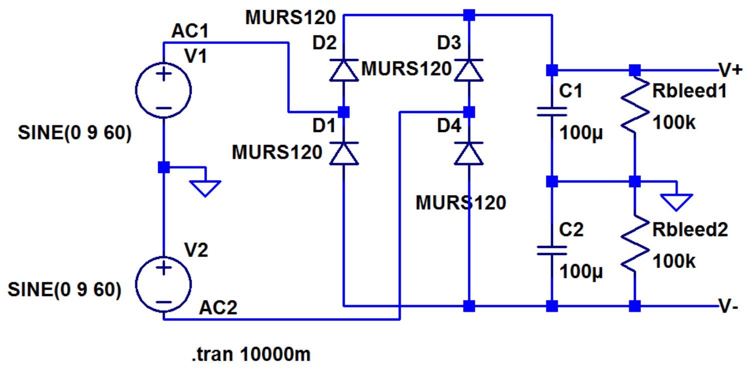

Figure 14. Dual supply simulation.

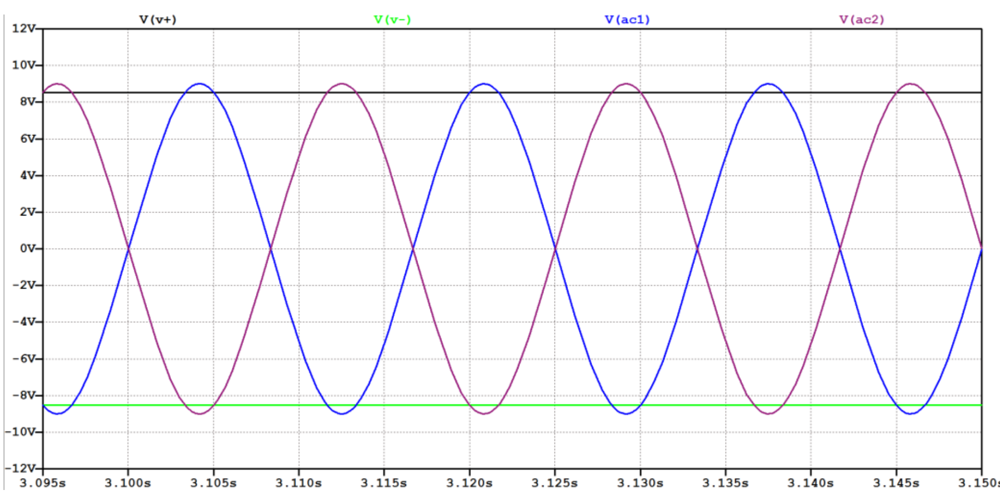

Figure 15. Positive and negative DC voltages and the two phases of AC from the center tapped transformer.

The problem with the power supplies that we have examined earlier is that they are unregulated. Unregulated power supplies can have significant changes in output voltage based on changes in the input voltage and in changes in the load. This is fine for many applications where the exact loads are known and accounted for. Audio amplifiers are also usually designed to operate over a wide range of supply voltages. For applications which require a closely defined voltage, a regulated power supply is needed. The easiest way to do this is with three terminal linear voltage regulators. The MC7800 positive and MC7900 negative regulator series are the most popular. The last two digits indicate the output voltage. For example an MC7805 is a positive 5V regulator and a MC7912 is a negative 12V regulator.

These regulators come in the TO-220 package which is good for heat dissipation. The pinouts are shown below in Fig. 16. Note that the positive and negative series have different pinouts. This is because in an IC, the most negative voltage has to be connected to the substrate which is usually also connected to the exposed metal tab on the package itself. Therefore the 7900 series swaps the ground pin for the input pin (the most negative voltage). These regulators usually have a minimum input and output capacitances for stability indicated in the datasheet. Any value above the minimum can be used. In this lab, 10 uF capacitors are used as shown in Fig. 17. To create a regulated dual supply, the outputs from the circuit in Fig. 14 can be connected to the inputs of Fig. 17. Please note that the input capacitors can be omitted from Fig. 17 if the filter capacitors from Fig. 14 are within a few inches of the regulators. If the distance is greater than this, the input capacitors should be left in the circuit.

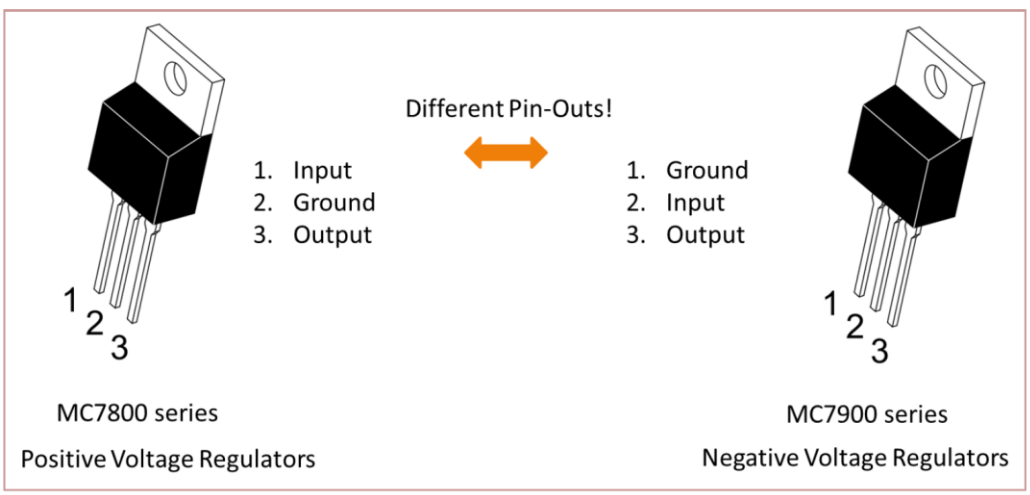

Figure 16. Pinouts for MC7800 and MC7900 regulators.

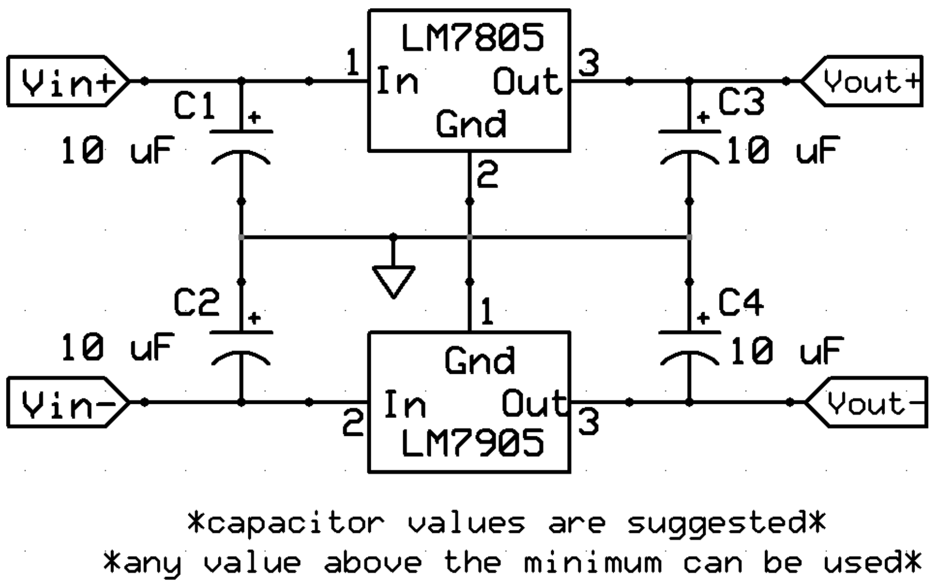

Figure 17. Using linear regulators to create a dual supply.

The main disadvantage of linear regulators aside from heat is that the input voltage must be higher than the output voltage by a minimum amount for the regulator to operate correctly. A table of the most important characteristics from the datasheet of the 7805 is shown below in Table 1. The dropout voltage is how much the input needs to be higher than the output. For a 5V regulator, this means that the input voltage must be at least 7V or higher. From the simulation it seems that our input voltage of 8.5V is high enough with a sufficient margin.

Characteristic (7805)	Symbol	Min	Typ	Max	Unit
Maximum Input Voltage	V_I			35	V
Dropout Voltage	$V_I - V_o$		2.0		V
Quiescent Current	I_B		3.2	6.0	mA
Peak Output Current	I_{max}		2.2		A
Power Dissipation	P_D		Internally Limited		W
Thermal Resistance (Junction to Ambient)	$R_{\theta JA}$		65		$°C/W$
Output Resistance	r_o		0.9		mΩ
Short Circuit Current Limit	I_{SC}		0.2		A
Line Regulation (7.3V to 20 V)	Reg_{line}		4.5	10	mV
Load Regulation (5mA to 1.5 A)	Reg_{load}		1.3	25	mV
Ripple Rejection	RR	68	83		dB

Table 1. Summary of the most important datasheet parameters for a linear regulator.

Prelab: You must include netlists and PCB layouts for each analysis.

Analysis 1: Bridge Rectifier

Design a bridge rectifier circuit as shown in Fig. 11. Assume that the load is drawing 100 mA and select the minimum filter capacitor size to keep the ripple voltage within 100 mV peak to peak.

Assume a 9 VAC peak source and calculate the DC output voltage of the circuit. Be sure to include the diode drops.

Simulate this circuit and create a plot similar to Fig. 12. You will have to find the correct load resistor value that causes 100 mA to flow based on the output voltage. This is because the simulated output voltage may differ from your calculated value.

Analysis 2: Dual Supply Bridge Rectifier

Create a dual supply bridge rectifier similar to the one shown in Fig. 14.

Simulate the circuit and ensure that the plots look similar to the ones in Fig. 15. Use 100k for the bleeder resistors and use the same values for the filter capacitors that you calculated in the previous analysis.

Connect a load between the positive rail and ground and the negative rail and ground. Each load should draw 100 mA for a total circuit load of 200 mA. You will use two resistors to represent the loads. Calculate the minimum filter capacitors needed to keep the ripple voltage within 100 mV peak to peak. You only have to do one calculation and then place that filter capacitor value in both the positive and negative portion of the power supply. Verify this with a simulation.

Lab Experiments:

Experiment 1: Unregulated Dual Supply

1. Verify that the transformers given to you are working. You should do this with the AC voltage setting on the multimeter and ensure that both the positive and negative outputs of the transformer give the correct voltage when referenced to the center tap. Place the negative multimeter probe into the center tap of the transformer. Use the positive multimeter probe to measure the voltages on the remaining outputs of the transformer. Be sure that these voltages measure fairly closely. For example a 6.3-0-6.3 transformer, each

side should measure 6.3 V. If there is a big difference or you measure no voltages it could mean the transformer is damaged.

2. Design the power supply for a load current of 20 mA. Size the filter capacitors for this load current. Calculate the correct load resistor to result in a load current of 20 mA for each rail. This resistor will get hot, but it will be within the 0.25 W dissipation limit of the resistor. Use 100k for the bleeder resistors.
3. All measurements in this lab are made referenced to the center tap of the transformer. Ensure that the center tap of the transformer is connected to your circuit ground. This will ensure that the circuit and the measuring equipment have the same ground potential. Measure the DC voltages with no load connected and verify that the power supply is working correctly.
4. Connect the load resistors and measure the resulting ripple on the oscilloscope. It is a good idea to AC couple the oscilloscope so that the DC component is removed and the ripple is clearly visible.

Experiment 2: Regulated Dual Supply

1. Add linear regulators as shown in Fig. 17 to the unregulated dual supply. Be sure to remove the load resistors. The bleeders can be left in the circuit.
2. Measure the DC output voltages with a multimeter or on the scope to ensure the circuit is operating correctly.
3. Try to measure the ripple voltage. It may be below the resolution of the oscilloscope.
4. Next add LEDs as shown in Fig. 18 below. This circuit is running the LEDs very hot so that the regulators show some ripple voltage. Because of this, do not leave the circuit on for more than a few minutes at a time. Use either yellow or green LEDs.
5. Measure the ripple voltage from the regulators.

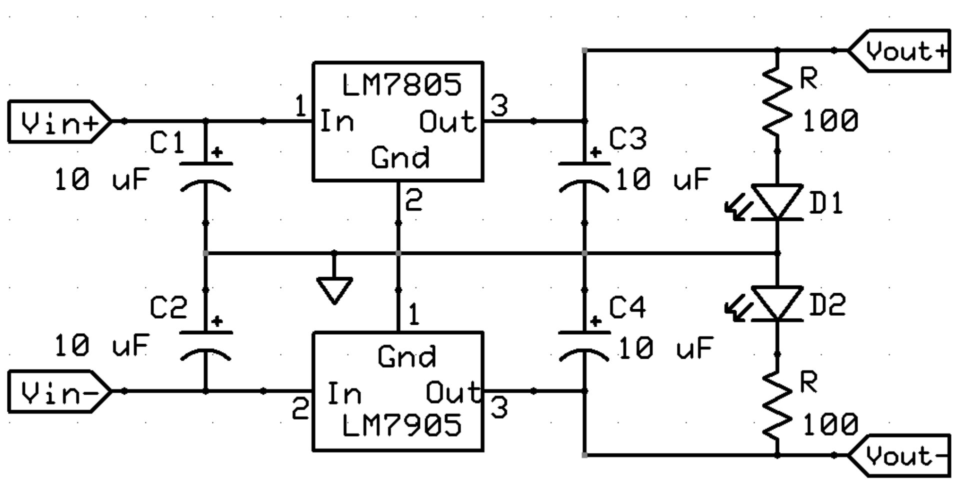

Figure 18. LEDs as loads.