
SECTION TWO

Rectifier and Filter Design

SECTION OVERVIEW

This section deals with rectifier and filter design. Following are the objectives, materials and design constraints for this lab.

Objectives

- Become familiar with the device characteristics of diodes.
- Understand the design trade-offs between half and full-wave rectifiers.
- Design and build your own rectifier and filter for your power supply that meets the design constraints.

Materials

- Oscilloscope probe, BNC to alligator clips cable, and test leads.
- Solder-less breadboard and jumpers.
- Your lab parts kit.
- MatLab or similar graphing program.
- Your textbook, *Sedra and Smith*, for reference: *5th Ed.* Pages 174-182 or *6th Ed.* 195-204.

Design constraints

Box 2 lists some of the design constraints for your final power supply that will apply to the AC-to-DC rectifier block. Be sure that you know all of the constraints and requirements to avoid confusion. These are always listed in the *Project Specification Document*. Keep these in mind as you complete this lab. Each criterion must be met.

- Two channels, one positive and the other negative when referenced ground.
- Each channel must be capable of supplying at least 900mA per channel continuously at voltages between ± 2 and ± 12 V.
- Current limiting circuitry for each channel, protecting above 1 A +/- 10%.
- Voltage ripple less than $0.75V_{p-p}$ per channel, with both channels fully loaded to 900mA.
- Easily accessible AC power switch.
- A clearly visible power indication light.
- Power supply assembled safely and with no electrical hazards and utilizes a safety fuse.

Box 2: Final power supply design constraints



This section makes several references to various AC voltages. In this section, the AC voltages are RMS values. However, you should be aware that AC voltages are sometimes given in peak-to-peak values.

PRE-LAB

This lab and every lab after it, will require a pre-lab assignment to be completed, prior to your scheduled lab time. You will be required to show the work you did, and sometimes it will be turned in for a grade. This work is an important part of each lab and will be graded. Not having any part of your pre-lab done at the beginning of lab will result in a loss of all pre-lab points.

1. Read pages 195-204 (or 172-184 in 5th edition) in your text. Understand how a half-wave and full-wave rectifier works. Understand how a capacitor is used smooth the rectified AC. Become familiar with Figure 4.20 (Figure 3.24 in 5th edition) of your text book. In this section, you will be designing and building the blocks labeled “Power transformer”, “Diode rectifier”, and “Filter”.



Bring a copy of the 1N4004 diode datasheet.

2. Derive or find the equation for voltage ripple (in your text) in half-wave and full-wave voltage rectifiers. In MatLab, or a similar program, plot the theoretical voltage ripple amplitude vs. the filter capacitor size (i.e. log plot 1nF to 1F), for a half and full-wave rectifier with:
 - Load Current: 1 A.
 - Source Frequency: 60 Hz
 - Source Amplitude: 24 VAC

LAB

This lab is divided into six parts: **diode device characteristics, half and full wave rectifier design, rectifier and filter for your power supply, transformer/ wall outlet output resistance, power indicator LED, and connector hardware.**

Part One – Diode device characteristics

An ideal diode acts as a short to current flowing in the forward direction, and acts like an open circuit to current flowing in the reverse direction. A real diode has finite resistance. A diode’s resistance is non-linear. A common characterization of diodes is a graph to relate the current flowing through a diode as a function of the voltage across it. This is referred to as an “I-V” curve. The slope of this line is admittance, or 1/resistance. A resistor’s I-V curve is a straight line.

In Part One, you will learn to: **measure the I-V characteristics of a 1N4004 diode**, as well as to **measure r_d of your 1N4004 diode.**

Measure the I-V characteristics of the 1N4004 diode

In order to measure the I-V characteristics, follow these steps:

1. Build a circuit, as shown below in Figure 4, which consists of a 1N4004 diode and a resistor to control the current. (It might be easiest to use half of a potentiometer).

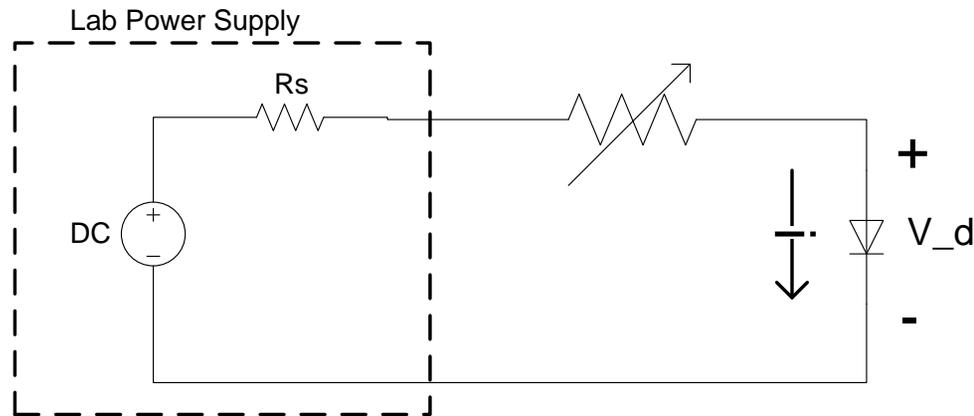


Figure 4: Diode Testing Schematic

2. Set your lab power supply to 3V and attach it to the circuit.
3. Measure the voltage drop across the diode and the current flowing through it. Take at least 10 sets of data from 0 – 100 mA. Open up Excel or MatLab at your workstation and record the data directly while you work. Take enough data to accurately reproduce the non-linear I-V characteristics.
4. Plot your data.
5. Now, answer the following:
 - a. Do your measured values look like what you expected?
 - b. Is it accurate to use 0.7V as an approximation of forward voltage drop for your diode?
 - c. If not, what range of currents would this approximation be useful for?
 - d. What is the forward voltage drop reported on the datasheet?

Measure r_d of the 1N4004 diode

Notice that r_d is the small signal resistance of the diode. Typically the voltage across a diode is a large DC bias plus a small variation from this bias. When working with small signals, it is convenient to use a linear approximation of the I-V characteristics of a diode, thereby approximating the response of the diode to small signals as purely resistive. For this approximation to hold, the small signal must be much less than the DC bias, (i.e. typically <10% of the DC bias).

In Figure 5, the bias or Q-point is the intersection of V_{dQ} and I_{dQ} . The linear approximation (solid line) applies for small signals superimposed upon the DC bias.

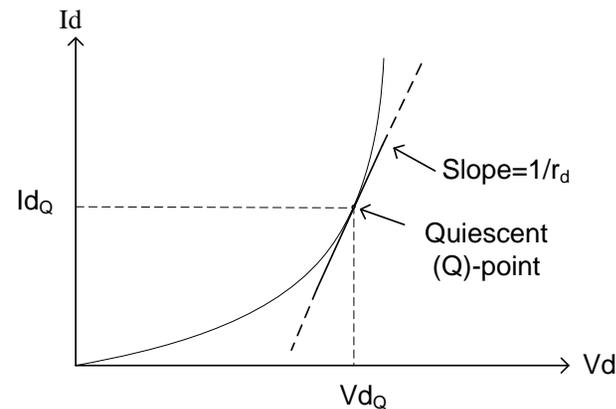


Figure 5: Q-point and r_d

In order to measure r_d of the diode, follow these steps:

1. Bias your diode with currents of 1mA, 10mA, 100mA, and 500mA DC.
2. Make a small change, (in either direction) in the bias current, and record the corresponding change in diode voltage.
3. Use these current and voltage data sets to estimate r_d for each bias current.

The definition is:

$$r_D(I_{DC}) \equiv \lim_{\Delta I \rightarrow 0} \frac{\Delta V}{\Delta I} = \frac{dV(I_{DC})}{dI}$$

4. Does small signal resistance r_d increase or decrease, as bias (DC) current is increased?

Part Two – Half and full-wave rectifier design

The process of converting AC to DC is called rectifying. There are two basic types of rectifiers: the half-wave and the full-wave. In this section, you will be designing and building both.

The output of a rectifier is typically filtered to make the output as smooth as reasonably possible. However, despite filtering, the output varies significantly under higher currents: hence, a voltage regulator is normally used in addition, when a stable voltage supply is required.

Design and build a full-wave rectifier

In order to implement the above, follow these steps:

1. Design and build a full wave rectifier that will convert 60Hz 10VAC_{0-p} to DC, to support a load that draws 1mA. Design the rectifier to have less than 1V_{p-p} ripple voltage. If you are having trouble, you may want to modify your simulation in Section One for these specifications and verify your design.
2. Generate the AC using the signal generator and use resistors to create a 1mA load.
3. Measure the DC output using the DC coupling mode of the oscilloscope.
4. Measure and record the ripple voltage and frequency using the oscilloscope.
5. Now, answer the following:
 - a. Are you able to measure peak voltage in both DC and AC coupling mode?
 - b. Is it easier to measure the ripple voltage in DC or AC coupling mode?
 - c. Your ability to make ripple voltage match your design calculations is limited by the tolerance of the capacitor, (which is often as high as $\pm 20\%$). Were you within 20% of what you calculated for ripple voltage?

Design and build a half-wave bridge rectifier

In order to implement the above, follow these steps:

1. Convert your full wave rectifier design to a half wave bridge rectifier. Use the same capacitor as you did in the full wave rectifier.
2. Use the signal generator to create the AC, and a variable resistor to create a 1mA load.
3. Measure and record the peak DC voltage and peak ripple voltage.
4. Now, answer the following:
 - a. Based on your measurements, which rectifier would you choose to use to support the load?
 - b. What design trade-offs does your chosen rectifier type have, compared to the other type? (Think about comparisons of price, reliability, time to build, quality of the DC, and why you might use each type of rectifier).
 - c. Which parts are the most expensive and how does this contribute to your choice of rectifier type? (Part numbers are included in *Appendix C: Parts*).

Part Three – Rectifier and filter for your power supply

Your power supply will need to convert 60Hz 120VAC_{rms} down to a usable 2-12V DC. The first step is to step down or reduce the AC voltage to 24VAC_{rms} using a transformer.



You may want to refer to your *Electrical Fundamentals II (ENGR 202)* notes for information regarding transformer. Specifically, you will want to be familiarizing yourself with transformer turns ratios and center-tap transformer.

You should now be able to analyze and answer the following questions:

1. If the secondary windings can pass up to 1A of current, what is the maximum primary side current that can be supplied?
2. You will be using the center tap on the secondary side as your power supply ground. What voltage will be present on the other two leads of the secondary side, (which is referenced to your power supply's ground).
3. The transformer included in your kit can support both 115VAC and 230VAC on the primary side. For 115VAC supply, you use the primary side center tap (yellow) and one of the end wires (black). What would your turns ratio and output voltage be, if you accidentally connected 115VAC across the outer two leads, and did not use the center tap on the primary side?

Section Two: Rectifier and filter design

Part Three has been divided into the following sub-sections: **design, lead usage of the transformer, electrical safety, and assembly of the power supply.**

Design

Now that you have constructed a few examples of rectifiers, you will need to implement the design that you created in your pre-lab, by observing the following:

- Select an appropriate value for the filter capacitor.
- Be sure that your rectifier meets the specifications for the sub-block, so that your power supply will be a success.
- Remember that the input voltage was about 24VAC, as per your assumptions in the pre-lab.
- You will use the included transformer in your kit to convert the 120 VAC of the wall outlet down to this 24VAC.
- You can use the schematic (in the next sub-section: Figure 6), to help you in using the transformer.

Lead usage of the transformer

Figure 6 is a schematic that illustrates the usage of the transformer.

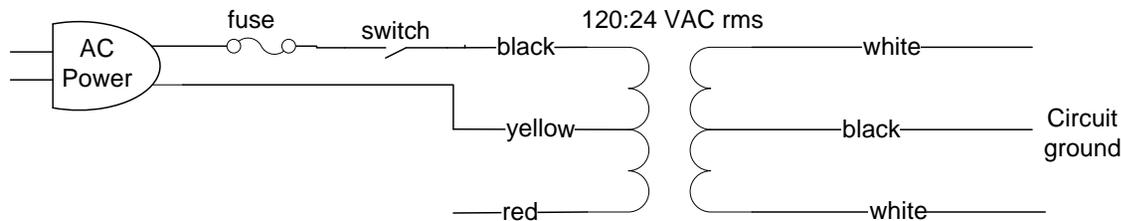


Figure 6: Schematic of transformer usage

The primary side center-tap will not be utilized. However it is still energized and must be safely terminated. Figure 7 illustrates proper termination using heat shrink wrap.

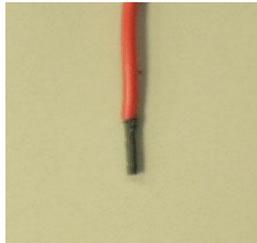


Figure 7: Safely terminated wire

Electrical Safety

In this section, you will be building circuits that will be energized by high voltage AC. Implement the safety instructions in the following caution-table before moving further:



1. Ensure that all leads and connections are secure, and that they are covered with heat shrink to insulate them.
2. You must also solder the fuse holder to the black lead of the power cord.
3. **Do not** energize this circuit, until your TA has approved the safe assembly of your circuit.
4. **Do not** forget to follow the “one hand” rule that was covered in Section One.

Refer to Figure 8 for an example of how to safely make connections for your high voltage leads. The power switch and fuse have been installed on the primary side of the transformer.

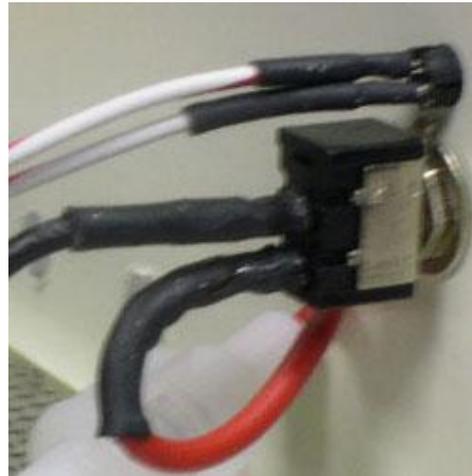


Figure 8: Safely made connections for high voltage

Assembly of the power supply

Before you place any components, you should have a good idea as to where you want to place all of the components. See Figure for an example of how you might arrange the components. Place your components inside the empty case to get an idea of where you want to place everything.

To help you along, this manual will give you suggestions about where to place your various components on the prototyping boards. You do not need to exactly follow these suggestions, but be aware that you will need to fit quite a few things into your supply case.

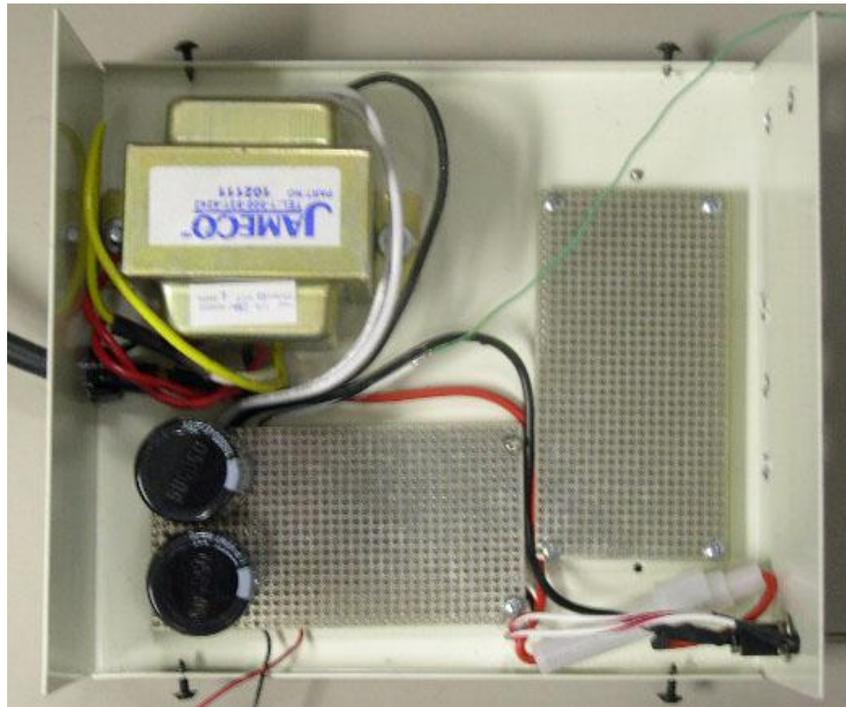


Figure 9: Example layout of the power supply components

Build your rectifier and filter circuit on one of the circuit boards in your lab kit.

You will want to make sure the transformer wires are soldered securely.



Be careful that no part of the circuit protrudes so far that it may come in contact with the aluminum base or one of the screws.

Part Four - Transformer/ wall outlet output resistance

Your transformer incurs losses at high currents. How do you know this? (**Hint:** Power losses often produce waste heat). This implies that the transformer has finite output resistance. The wall outlet also has finite output resistance.

In this section, you will need to do the following:

- Make an estimation of the output resistance of the transformer.
- Make an estimation of the output resistance of the wall power outlet.

Part Five - Power indicator LED

This is a good time to include your power indicator LED. In order to do this, follow these steps:

1. Size your resistor, such that the maximum forward current of the LED is not exceeded, but is still sufficient to light the LED.
2. Remember that the voltage can get as high as 18 VDC when the power supply is not loaded.
3. Refer to the LED data sheet to get this information.
4. You will want to pay attention to which supply you use, (either the negative or the positive supply), as it will affect the direction in which to insert the LED.

Part Six - Connector Hardware

You may use a drill to create mounting holes for all of the components. Suggested drill sizes are shown below:

- Power cord – 5/8"
- Circuit board holes – 1/8"
- Power LED – 3/16"
- Transformer screws – 1/4"
- Power switch – 1/4"
- Binding posts – 5/16"
- Potentiometers – 5/16"

If you have never used a drill before, then ask someone to show you how. But do not let them drill all your holes for you and take away the satisfaction of a job well done.

Have fun assembling your power supply. Go slowly when necessary and feel free to ask questions of your group partner when you don't understand part of this section. Other groups are also a good source of help, but do not share specific component values. Your TA is always able to help you, if needed.



The filter capacitors will remain charged even after the unit is unplugged. It will take a 2K Ω resistor about ninety seconds to discharge the capacitors.

STUDY QUESTIONS/ TURN-IN

In addition to study questions and documents to turn-in, this section introduces you to the project specifications that will be included henceforth as part of your ‘turn-in documents’.

Project Specification:

As mentioned before, you are building a power supply that meets a project specification document. For many of the following labs, you will be reminded to update the project specification with your schematics and information. Since this is the first time you have done this, go to the Web-page and download a copy of the *Project Specification Document*.

In Section 6 of the document, there are places to enter information about the various schematics for each sub-block. You will need to complete this section and update other portions of the specification. From the next lab time, you will need to turn in a copy of the sections that you have updated in the preceding week. To help you this one time alone, you get a heads-up on which sections you need to update for this lab.

The following sections of the *Project Specification Document* need to be updated:

- Section 6.2 – AC Rectifier Block
- Section 8 – Parts List and Costs Analysis
- Section 1 – Revision History

TURN-IN

The following need to be turned in, **at the beginning of the next lab (Section Three).**

Student Name: _____

Lab Section Time: _____

<u>Test (from Project Specification)</u>	<u>Measurements</u>	<u>TA Signature</u>
<u>7.1.1 - AC RECTIFIER - TWO CHANNELS, ONE POSITIVE AND THE OTHER NEGATIVE WHEN REFERENCED TO GROUND</u>		✓ _____
<u>7.1.2 - AC RECTIFIER - RECTIFY 60Hz, 120 VAC_{RMS} TO DC</u>		✓ _____
<u>7.1.3 - AC RECTIFIER - CAPABLE OF SUPPLYING AT LEAST 900mA AMP PER CHANNEL CONTINUOUSLY</u>		✓ _____
<u>7.1.4 - AC RECTIFIER - VOLTAGE RIPPLE OUT OF THE FILTER IS LESS THAN 0.75V_{P-P} PER CHANNEL WITH BOTH CHANNELS FULLY LOADED TO 900mA</u>		✓ _____
<u>7.1.5 - AC RECTIFIER - EASILY ACCESSIBLE AC POWER SWITCH</u>		✓ _____
<u>7.1.6 - AC RECTIFIER - A CLEARLY VISIBLE POWER INDICATION LIGHT</u>		✓ _____
<u>7.1.7 - AC RECTIFIER - ASSEMBLED SAFELY AND WITH NO ELECTRICAL HAZARDS AND UTILIZES A SAFETY FUSE</u>		✓ _____

The **written project specification** to be turned in next week includes:

- Project Specification Sections for this lab's circuits:
 - Block Diagram

Section Two: Rectifier and filter design

- Interface Definition
- Schematic and theory of operations
- Parts List Changes and Testing Results

The **prelab** to be completed (before lab begins next week), includes:

- Prelab for Section Three.

Lastly, turn in your **answers to the study questions** below.

Study Questions:

Please write your answers to the following set of study questions on a different sheet of paper. You may type your answers, or write them neatly by hand. Keep your answers clear and concise.

- a. At what voltage does current begin to flow through your diode in Part One of this section?
- b. If you designed a circuit that used the forward voltage drop of your diode as a voltage reference, what voltage would be provided with a forward current of 10mA?
- c. The values that you measured for peak and ripple voltage were different between the half and full wave rectifier from Part Two. What was the difference in the peak voltages? What causes this difference?
- d. What was the difference in the ripple voltages? What causes this change?
- e. How do your ripple measurements of your full bridge design of Part Three compare with the PSPICE simulation? What can explain the differences?
- f. Comment on the significance of the output resistance of the transformer and wall outlet on the output voltage in your PSPICE simulation under high load currents (1A).

CHALLENGE

The I-V curve of a diode is not always the same. Recall that in *Electronic Materials and Devices (ECE 317)*, you learned that the current through a diode depends on device characteristics that vary with temperature.

Bearing that in mind, analyze and answer the following questions:

1. Describe the effect temperature has on a diode at the atomic level.
2. Plot additional I-V curves for your diode with significant changes to temperature. You could use 32°F (0 °C) and 212°F (100 °C), as these are easy to maintain accurately during testing. Use as many temperatures as needed to accurately predict the shift in the I-V curve. Ensure the current is not so high that it causes the diode to heat up on its own.
3. Explain how the shift in the I-V is explained by your answers to Question #1.
4. Using plots of the I-V curves, create a method to easily measure temperature with a diode.
5. Use the .TEMP function in PSPICE to simulate elevated temperatures. Plot the I-V simulation result under various temperatures.

To get extra credit for the challenge problem submission, you will need to turn-in the following:

- A typed report containing your answers to the above questions.
- Any additional I-V plots that you created.
- An explanation of how a different diode, or even a transistor, might be more suitable than the diode that you chose for your design.