EE283 Laboratory Exercise #8
Transformers, Diodes, Rectifiers, and Power Supplies

Objectives:

1. To become familiar with the I-V characteristics of rectifying and Zener diodes.
2. To understand and construct linear DC power supply and regulator circuits.

Theory:

1. **Diodes**: Diodes are two terminal electrical components that exhibit directional, nonlinear, current versus Voltage (I-V) characteristics. The circuit symbol and a typical I-V curve are illustrated in Figure 8.1. Forward biased diodes allow current to flow with only a small effective (but nonlinear) resistance, while revere biased diodes have only a very small leakage current up to the diode's peak inverse Voltage (PIV). A PIV of hundreds of Volts is common. The 1N4004's we will use have a rating of PIV=400V. (That's high enough to be useful directly rectifying 120V AC to DC.) Diodes in the KV range, such as those used in microwave ovens, are usually physically smaller diodes in series. (Don't do that with discrete diodes without special precautions to distribute the Voltage evenly.) Going beyond the PIV rating can cause enormous heat dissipation in the diode (P=VI) and usually destruction of the diode as well as, perhaps, other components. A band on the diode identified the Cathode, the terminal towards which current flows if forward biased.

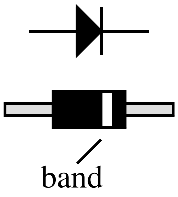


Figure 8.1(a) Symbol and diode appearance

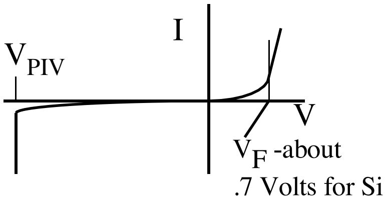


Figure 8.1(b) Typical diode I-V curve

A rectifier diode (or signal diode, designed for small currents and fast switching) typically break down at well above the rated PIV for the component. In contrast, Zener diodes are designed and manufactured to break down fairly precisely at a given Voltage. They are often used in circuits where current flows in the direction opposite the diode arrow, and they serve to hold the Voltage across them fairly constant at that Zener Voltage. They essentially serve as Voltage sources, with the caveat that the current must remain negative. Figure 9.2 gives the symbol and a typical I-V curve for a Zener diode. Zeners physically look like other diodes, but are often larger because in many practical circuits they need to dissipate more power.

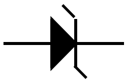


Figure 8.2(a) Zener diode symbol

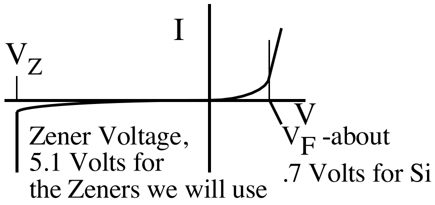


Figure 8.2(b) Zener diode I-V characteristic

2. Transformers:

A transformer can be thought of as an inductor with two windings. In a tightly coupled transformer of the type used for power handling, the Voltage across the two (or more) coils is proportional to the number of turns on each winding, neglecting resistance losses in the copper wires and a small loss of power in the transformer's iron core connecting the windings magnetically. The symbol a transformer is shown in Figure 8.3 below. For power supply use on small scale, the primary Voltage is controlled by the Voltage source, typically 120 Volts (rms) at 60 Hz drawn from utility outlets. The turns ratio then determines the secondary Voltage. If a transformer has 300 turns for the primary winding, and 30 turns for the secondary winding, then if used normally with 120 Volt AC it would be called a 12 Volt power transformer. The black dots at the ends of the windings indicate which terminals go positive together at the same time, that is, they are in phase. The secondary often has a "Center Tap" that divides the secondary into two equal Voltages, 6 Volts and 6 Volts in this case. (Other types of taps are sometimes seen.)

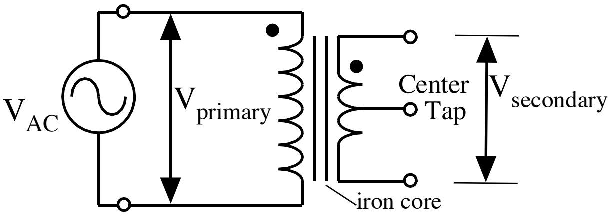


Figure 8.3 A Transformer, schematic symbol

In practical circuits, there would usually be a power switch and fuse in series with the transformer on the "hot" side of the primary. The protective ground might be connected to the transformer core as well as the equipment chassis. If you are going to build power supplies, safety issues outside the scope of this Laboratory exercise must be addressed, such as strain relief for the power cord, physical arrangements, and proper color coding. (Many low Voltage transformers use black for the primary, green for the secondary. A yellow secondary usually means high Voltage isolation from the primary. Red is often used for high Voltage secondaries.)

3. Rectifier Circuits:

A “half-wave” rectifier circuit allows current to flow in one direction and not the other, so that only the positive (or negative, depending on diode orientation) can appear on the other side of the diode. A “load” that is being supplied by the diode is represented by a resistor.

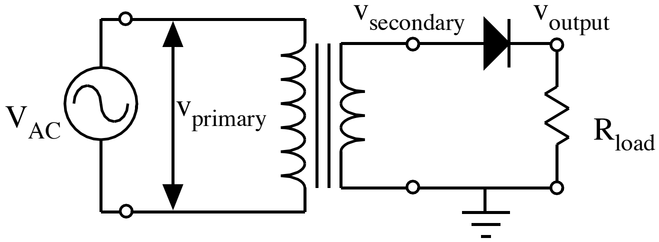


Figure 8.3(a) Half Wave Rectifying Circuit

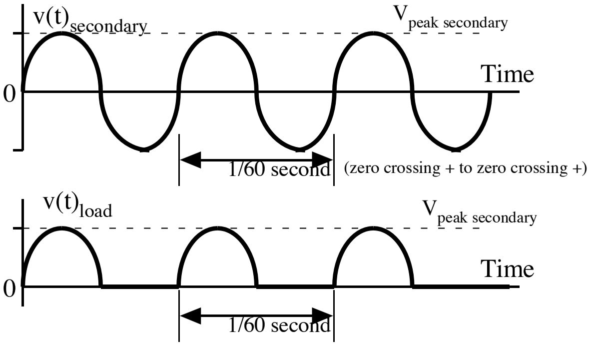


Figure 8.3(b) Half Wave Rectifier Output

Note that the half wave gives a pulse once per cycle, and is actually zero half of the time, the part of the cycle where the diode anode Voltage swings negative. While this would register as a DC Voltage on a meter, an AC meter would register considerable AC Voltage as well. If you want pure DC, this is NOT a good circuit as it is. (The peak output Voltage is a bit lower than the secondary Voltage peak due to the forward Voltage drop in the diode, often about .7 Volts or a bit more.)

A “full wave” rectifier circuit can be contrived using a center tapped transformer. The center tap is grounded, and both ends of the winding are connected to the load through a diode. Whichever way the waveform swings, one diode or the other will conduct. The catch is, the peak Voltage out is a bit less than ½ of the AC peak, because for each phase only half of the transformer is being used. So, if you wanted about 17 Volts peak out, you’d use a 24V VAC secondary transformer, because ½ of 24V is 12 Volts, and that’s multiplied by 1.414 (sqrt 2) to get 17 Volts. With the diode drop, you’d get a peak Voltage out of about 16.2 Volts. Note that Neither <u>end</u> of the secondary is grounded! The load goes back to ground, the center tap.

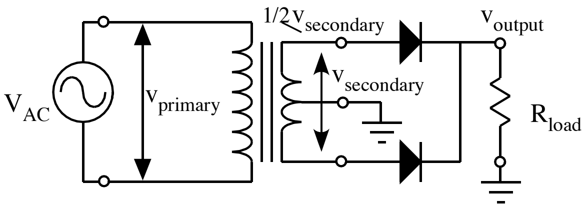


Figure 8.4(a) Full Wave Rectifying Circuit

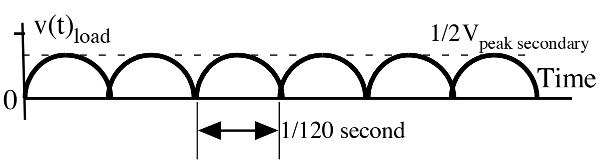


Figure 8.4(b) Full Wave Rectifier Output

A second "full wave" rectifying circuit can be used if there is no center tap. In this case, the peak of the load Voltage is a bit less than the full secondary AC peak, but the circuit suffers from two diode losses instead of one. This circuit, with a grounded center tap instead of the negative terminal of the bridge, provides two equal valued full wave outputs, one positive and the other negative, each at one half the Voltage, as shown in Figure 8.5. Full wave bridge diode components, with four diodes and four terminals, are often used in practical power supplies. (We will build ours from discrete diodes.) Be absolutely sure that neither terminal of the transformer secondary is grounded! If it is, something will burn up.

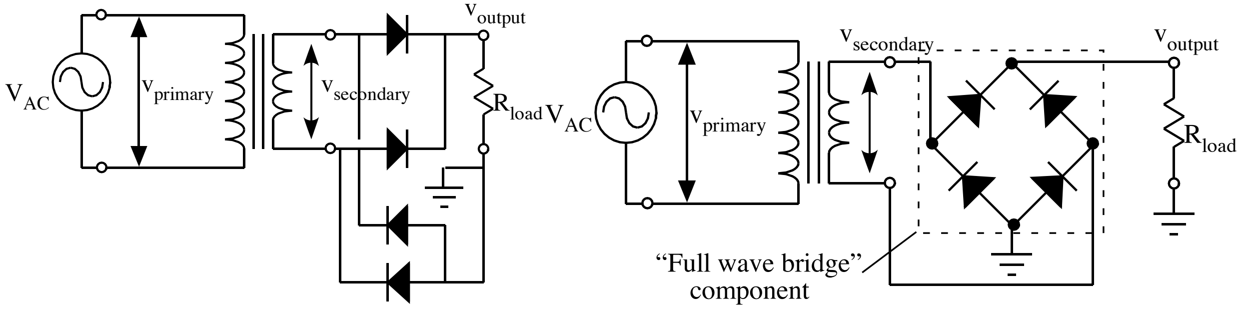
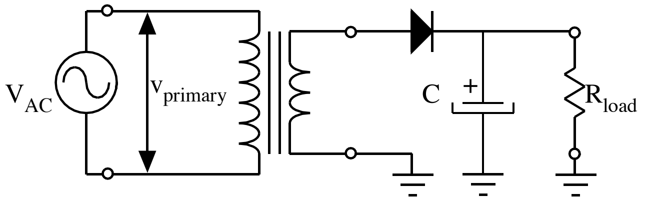


Figure 8.5 Two equivalent full wave rectifying circuits using a "full wave bridge" of 4 diodes

4. Filtering circuits:

Both the half wave rectifier and the full wave rectifier produce less than full, smooth DC. Both have a "ripple" Voltage that is easily detectable with a meter or the oscilloscope. Usually it is desirable for a DC power supply to have very little AC ripple. What is needed is a filter circuit. Specifically, we need an AC low pass filter which has a cutoff well below the ripple frequency, which is 60 Hz for a half wave rectifier, and 120 Hz for full wave.

The simplest form of filtering is to put a capacitor across the rectifier output, as seen in Figure 8.6(a). The capacitor charges rapidly when an AC peak comes along. Then, after the peak, it supplies all of the current to the load until the next peak comes along. This results in a waveform that is approximately a "sawtooth" form, as seen in Figure 8.6(b). We want the filter capacitor to be "big," so we usually use a polarized electrolytic capacitor, as seen by the symbol.



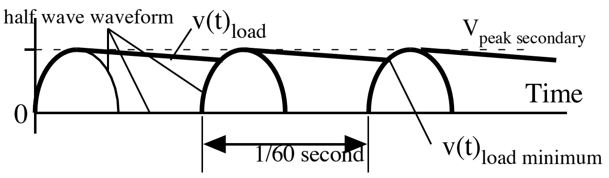


Figure 8.6(a) Capacitor filtered half-wave supply Figure 8.6(b) half Wave Filtered Waveform

The question is, “How big?” That depends on how much ripple you can tolerate. In this case, let us suppose that the output Voltage averages 16 Volts. The ripple Voltage is small, let’s suppose just .5 Volts would be tolerable. (Usually you’d want it smaller.) It is 1/60 seconds between peak pulses. We assume output current, which all comes from the capacitor during the downward ramp, is about constant. Suppose the load is 16 Ohms. Then the average current is 1 Ampere. A capacitor has the characteristic Q = CV, or i(t) = C dv(t)/dt. If we assume current is constant over 1/60 second, then 1A = C (.5V)/(1/60 sec). Solving for C, we get C = .0333 F, or, 33,300 μF. We would use the next commercially available value up from that, 50,000 μF.

If this was a full wave rectifier circuit instead of half wave, the period of the ripple would be 1/120 sec, and the needed capacitor would be only half as large. Diodes are usually cheap. Capacitors are relatively expensive. So, using a full wave bridge instead of half wave is what you’ll usually see. Only in applications where the diodes are expensive or ripple doesn’t matter much will you see half wave rectifiers. Those include battery chargers and microwave ovens.

Note that capacitors are sold in units of μF and pF and, for truly big ones, Farads. Units of mF or nF are not used in ordering capacitors, and you should not use units of nF or mF for your academic work, even though some textbooks and test equipment suppliers do use those units. Use of mF and nF can be a sign that the writer doesn’t understand the traditional conventions of the profession. (In older schematics, “mfd” means “microfarads” and “mmfd” means “micro-micro Farads,” the same as picoFarads. Hence, use of mF can be confusing.)

Other forms of filters are shown in Figure 8.7. Inductor input filters can only be used with full wave circuits. Inductors used in filters are often called “Chokes”. You don’t often see inductors in filters today; they are bulky and expensive, with cost comparable to transformers.

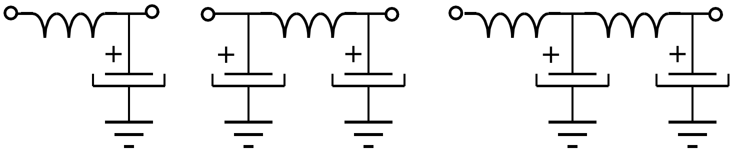


Figure 8.7 Other “Linear” filters.

5. Voltage regulation:

In addition to smoothing out any AC remaining after rectification, it is often desirable to make the output Voltage relatively independent of power Voltage fluctuations or load current. In the circuits shown, ripple will increase with load, and the average Voltage supplied dips. One simple circuit that can be used to regulate the output Voltage is a “shunt regulator” using Zener diodes. The Zener diode Voltage is the desired output Voltage. If the current through the regulator resistor, R, is greater than that drawn by the load, the excess current is dumped through the Zener. (That means that the Zener diode needs to be sized to dissipate $P = V_Z I_{max}$, where Imax is the maximum current through the resistor, with the load resistor disconnected. (Zeners are available in high Wattages, though usually better (series) methods are used if dissipation is going to be significant.) The resistor usually needs to be carefully specified for power as well. Figure 8.8 illustrates the shunt Zener regulator.

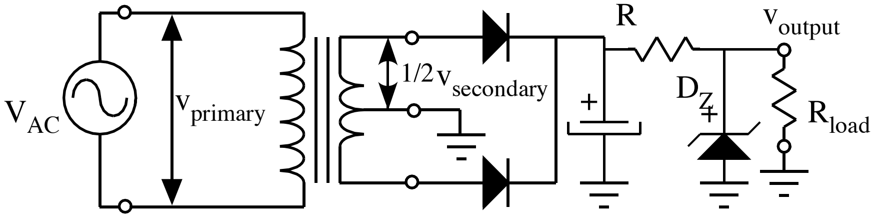


Figure 8.9 Shunt Regulator using a Zener Diode

The value of the Zener's Zener Voltage is simply the Output Voltage desired. The resistor is sized so that $R < (V_{Cminimum} - V_Z)/ I_{Lmaximum}$. The power rating should be $P_R \geq (V_{\text{minimum of the filter circuit}} - V_Z)^2/R$. If the load current might, under some circumstances, drop to zero, then the power rating of the Zener must be $P_Z = (V_R/R)\ V_Z$.

A better, but more complicated, regulator circuit is a "series" regulator. A low power shunt regulator is used to control what is, in effect, a "power op-amp". Understanding how to do the "Power op-amp part requires getting into transistor electronics, and that's beyond the scope of this course. For small amounts of power, a 741 Op-amp could be used. See the op-amp material in lab Exercise #9 for additional information about Op-amps.

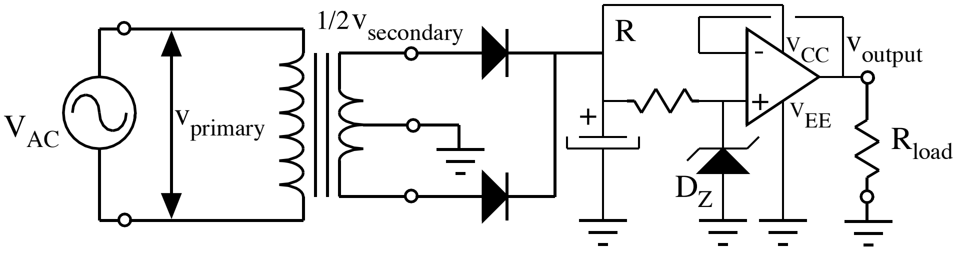


Figure 8.10 Series Regulator using a "Power" Op-amp

Monolithic three terminal series regulators for various Voltages are commonly and inexpensively available. Using such a device is quite simple. Pick the device for the output Voltage and power that you need, and simply put it into the circuit shown in Figure 8.11.

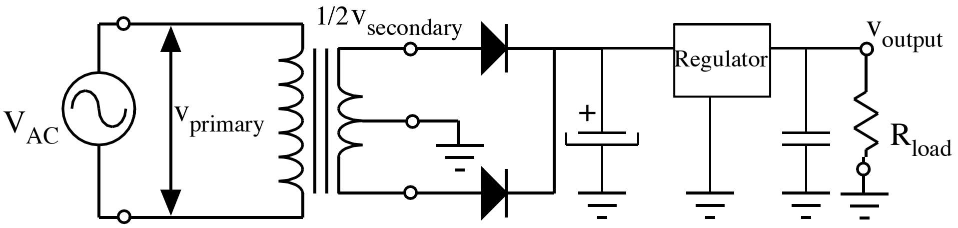


Figure 8.11 Voltage regulation with a monolithic series fixed Voltage regulator IC

Procedure:

1. Using the supplied transformer, plug in the primary side and measure the Voltages found on the secondary side. If you have a center tap, you want both the Voltage across the entire secondary and from the center tap to one of the other terminals. Measure the Voltage with the DMM and observe the waveform on the oscilloscope. Record RMS and peak to peak AC Voltages. Plot the waveform.

2. Build a “half wave” unfiltered DC rectifier using the transformer and a 1N4004 diode. Use a specified resistor value (500 Ohms is a default) as the load. Use the oscilloscope to observe both the transformer output and the diode output. Measure the load Voltage DC and AC components using the DMM. Plot the output waveform. (Note: V_{RMS} NOT = V_{p-p}/2sqrt(2) – not sinusoid!)

3. Build a “full wave” unfiltered DC rectifier using your transformer and 1N4004 diodes. If you have a center tapped transformer, build both versions, first using the center tap as ground and two diodes, then using the four diodes with the negative end of the bridge as ground rather than the center tap. Measure the load Voltage DC and AC components using the DMM. Plot the output waveform.

3. Add a filter capacitor to your full wave rectifier circuit (either one). Start with a 1uF capacitor, and see how it changes the waveform. Then substitute in 10µF, 100 µF, and 1000 µF capacitors. For each case, use the oscilloscope to observe the AC ripple Voltage. Use the DMM to observe the DC output Voltage. Calculate the ratio. Plot the output waveform for each case. You can put all four cases on the same graph.

4. Build a shunt regulator circuit, added on the filtered circuit above having the 1000 µF capacitor. Use a 100 Ohm resistor as your regulator resistor. Use two Zener diodes in series to get 10.2 volts output. Use a 1K Ohm potentiometer as a load in series with another 100 Ohm resistor, to allow the load to vary between 100 Ohms and 1100 Ohms. Vary the load resistance while observing the output waveform with the oscilloscope and the Voltage with the DMM. At

what Load (Resistance, current) does regulation “fail”? That is, the Output Voltage drops significantly below the desired 10.2 Volts out, and perhaps ripple appears? Plot the waveform at a load just below that point.

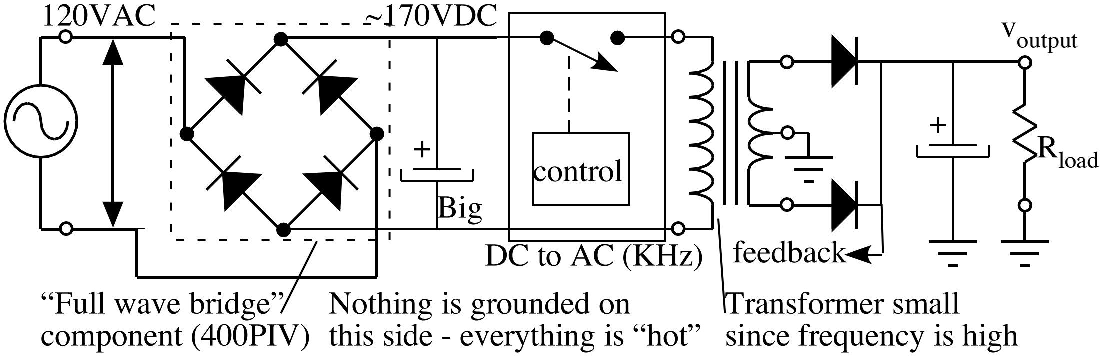
5. Extra credit: Build the series regulator circuit using your 741 Op-amp, and perform the same test of performance as used for the series regulator. Use R=10K Ohms for the regulator resistor R. Your Zener diodes will run much cooler! (You may run into the limits on the 741.)

Report:

Turn in the form report for this Laboratory Exercise. This form will have the results and measurements you obtained in the laboratory.

Comment:

“Linear” power supplies of the type described in this laboratory exercise are not used that often anymore. Transformers for 60 Hz power conversion are big, bulky, heavy, and expensive. Modern “switching” supplies are now more often used. Figure 8.13 shows a simplified circuit of a switching power supply. Essentially the supply consists of four parts: A DC full wave power supply that converts line Voltage to 170V DC with no transformer, A “chopper” circuit or some other circuit to convert the DC into AC at a high frequency (in the 10KHz region), A transformer to convert the AC to the desired Voltage range, and a full wave filtered circuit to put out smooth DC. Feedback from the DC output is typically used to regulate the supply by varying the switching waveform. The DC to AC circuit (and the control using feedback) is complicated. But, the transformer is small and light since it operates at a high frequency. The filter capacitors can be much smaller too. So, this much more complicated supply is smaller, lighter, and cheaper than a linear supply of the same rated Voltage and current.



“Full wave bridge” component (400PIV)

Nothing is grounded on this side - everything is “hot”

Transformer small since frequency is high

Figure 8.13 Simplified Example of a Switching Power Supply

EE283 Laboratory Exercise #8
Transformers, Diodes, Rectifiers, and Power Supplies Report

Students:________________________ Date: ___________________

______________________________________Section: Lab Station:

8.1 Transformer: unloaded Vout (AC$_{rms}$):________Vout (AC $_{peak-peak}$): _______

8.2 Draw half-wave circuit:

Half wave graph, diode input (transformer output) and diode output (to load)

Vout (DC): _______

Vout (AC$_{rms}$): _______

Vout (AC $_{peak-peak}$): _______

8.3 Draw full-wave circuit:

Full wave graph, diode input (transformer output) and diode output (to load)

Vout (DC): _______

Vout (AC$_{rms}$): _______

Vout (AC $_{peak-peak}$): _______

8.4 Draw full-wave circuit with capacitor filter:

Full wave filtered graph, diode input (transformer output) and diode output (to load) (4 traces)

With capacitor value:	V_{DC}	$V_{\text{ripple ACp-p}}$	ratio $V_{\text{ripple}} / V_{DC}$
1uF			
10uF			
100uF			
1000uF			

8.5 Draw shunt regulated circuit:

Shunt regulated waveform where regulation fails: (at R_{load} = ____ I_{load} =____________)