Power Supplies

PHYS 332

Abstract

In this lab you will construct DC power supplies using an AC power source. The first, a half-wave rectifier, will be analyzed qualitatively. The second, a full-wave bridge rectifier, will be analyzed quantitatively. You will investigate two characteristics of DC power supplies — regulation and ripple.

References:	Diefenderfer, *Principles of Electronic Instrumentation*, pp. 152–164
	Horowitz & Hill, *The Art of Electronics*, pp. 325–331
	Barnaal, *Analog and Digital Electronics for Scientific Application*, pp. A123–135

1 Introduction

AC signals consists of charge flow in one direction for half a cycle followed by charge flow in the opposite direction for the next half cycle. Every $\frac{1}{120}$ sec the current reverses. In contrast, the charge for a DC signal always flows in the same direction. There are two ways convert AC to DC: one, simply eliminate half of each AC cycle; two, change the direction of charge flow in half of each cycle. The part of the circuit that does this is called the *rectifier.* A *half-wave rectifier* produces the half-eliminated waveform and *full-wave rectifier* produces the half-changed waveform (see Figure 1).

Half-wave rectification is usually achieved by placing a diode in series with the load (here denoted by R_L). The polarity of the diode may be switched to obtain positive or negative signals (see Figure 2). Two common ways to obtain full-wave rectification are to use a center-tapped transformer (Figure 3) or a bridge circuit (Figure 4). Note that both ways make use of a transformer. This is done in order to reduce the voltage, since 120 volts DC can give quite a shock.

With the center-tapped transformer, the center is held at ground so that during the positive half cycle the diode, D_1, connected to the top of the transformer conducts while the diode, D_2, at the bottom end does not. During the next half cycle the situation is reversed. The voltage at the top of the transformer is now negative, so D_1 is turned off while D_2, now at the positive end of the transformer, turns on. Since both diodes are connected to the same side of the load, the voltage across the load is always positive. Note that the circuit in Figure 3 can be modified to produce negative DC signals by reversing the polarity of the diodes.

The bridge rectifier circuit in Figure 4 produces the same waveform as the center-tapped transformer. During the positive half cycle diodes D_2 and D_3 conduct, while during the

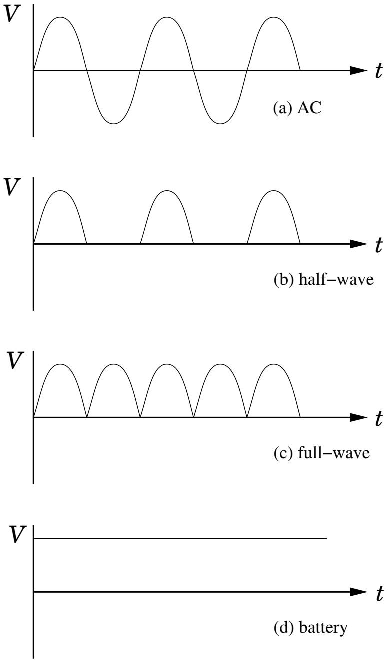

Figure 1: Diagram showing the waveforms produced by (a) an AC source, (b) a half-wave rectifier, (c) a full-wave rectifier, and (d) a battery..

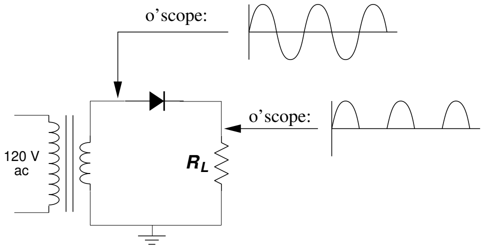

Figure 2: A simple half-wave rectifier with waveforms.

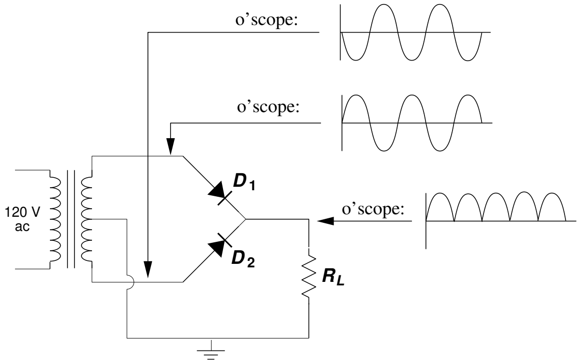

Figure 3: Full-wave center-tapped rectifier.

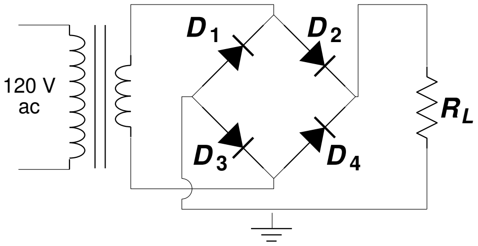

Figure 4: Full-wave bridge rectifier.

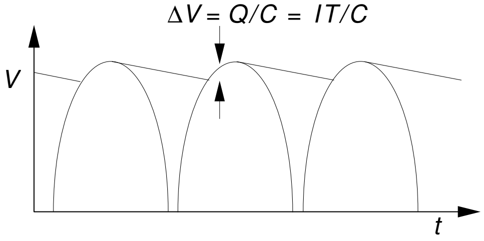

Figure 5: Filtered rectifier signal.

negative half cycle diodes D_1 and D_4 conduct. Whatever the polarity of the transformer voltage, the current is directed to go from the top to the bottom of the load resistor.

If we now compare the DC signal in Figure 1(b) or 1(c) to the output of a battery (Figure 1(d)), we see that we have not done a very good job of reproducing the battery's constant voltage. However, the rectifier signal can be improved by *filtering*: using capacitors, inductors, resistors, etc. to reduce the fluctuations in the voltage.

The rectifier signal can be thought of as an AC signal superimposed on a DC signal. The process of filtering attempts to remove the AC portion. This can be accomplished using two fundamental principles. First, a capacitor to ground offers a low impedance path to ground for the AC portion of the signal while maintaining a high impedance path for the DC portion. Second, because an inductor's reactance increases with frequency, a series inductor may be used to block AC signals while letting DC signals pass without much attenuation.

An RC filter is the simplest type of filter: it just uses a resistance and a capacitance. The resistance is just the load. The capacitance is chosen so that the capacitive reactance is much less than the load resistance at the ripple frequency ($\chi_C = \frac{1}{\omega C} \ll R_L$). Equivalently, the RC time constant must be very long compared to the period of the signal in order to remove most of the AC. This insures that the capacitor will not discharge very much before the next peak arrives. See Figure 5.

Power supply filters are designed to minimize the fluctuating signal (measured by $(V_{AC})_{rms}$) while leaving the constant signal (V_{DC}) unchanged. In turns out that as increasing currents (I_{DC}) are drawn from the supply (for example, by decreasing the load resistance R_L) the fluctuating signal increases and the constant signal decreases. For example, we will show that for a simple RC filter drawing small I_{DC}

$$(V_{AC})_{rms} \approx \frac{1}{2\sqrt{3}\,f\,C}\,I_{DC}$$

and that

$$V_{DC} \approx V_P - \frac{1}{2fC}\, I_{DC}$$

where V_P is the peak voltage and f is the ripple frequency (i.e., 120 Hz for a full-wave rectifier). Because the quantity $\frac{1}{2fC}$ has units of ohms, it is sometimes called the internal resistance of the power supply. Note that the DC voltage reduction is exactly equal to the voltage drop across this "internal resistance".

Power supplies are specified in terms of the worst expected behavior (which typically occurs as you approach the maximum output current). The maximum variation in output voltage as it supplies increasing current is specified as the *regulation* of the power supply.

$$\text{Regulation} = \max\left\{\Delta V_{DC}\right\} \approx \frac{1}{2fC}\,(I_{DC})_{max}$$

The ripple factor, r, is defined as the maximum ratio of AC to DC signal.

$$r = \max\left\{\frac{(V_{AC})_{rms}}{V_{DC}}\right\} \approx \frac{(I_{DC})_{max}}{2\sqrt{3}\, f V_{DC}\, C}$$

For a derivation of these expressions see the Theory section at the end of this handout. Note that both ripple factor and regulation increase (worsen) in proportion to the current drawn from the supply. Therefore, different power supplies must be compared at the same supply current (I_{DC}).

2 Experimental Procedure

You will be supplied with an electrical board which will allow you to study rectifiers and filters in different combinations. An oscilloscope will be used to look at the output signals of your power supplies. Generally you use scopes with DC coupling and that will be the case here when you want to view the entire signal, from 0 V to the peak. However, you will want to switch to AC coupling when viewing the ripple: removing the DC offset allows a more magnified view of the ripple. Generally you use scopes with triggering on one of the inputs, but here you are triggering on the 60 Hz line voltages, so you can switch triggering to LINE. Digital multimeters will be used to monitor the current and voltages. Be sure to check the multimeter's specifications for error estimates.

2.1 Half-Wave Rectifier

Connect the electrical board so that you have a half-wave rectifier. Connect the oscilloscope across the load and sketch the waveform. (Your scope trace sketches should always include the scale factors for the x and y axes.) Now add in a capacitor as a filter. Sketch the waveform. What happens to the waveform when you change the resistance of the load? Be sure to keep the DC current less than half an amp. What happens to the waveform if you add additional capacitors? Theory claims that twice the capacitance will halve the ripple. What do you find?

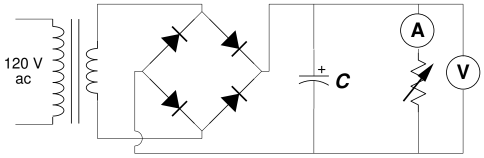

Figure 6: Full-wave bridge with simple RC filter.

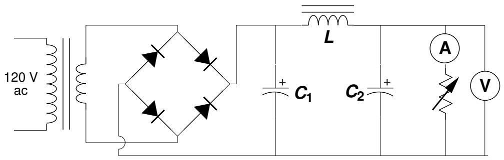

Figure 7: Full-wave bridge with a LC π-filter.

2.2 Full-Wave Bridge Rectifier

Connect the electrical board so that you have a full-wave bridge rectifier. Again look at the waveform on the oscilloscope and sketch it. Record the period, T, of the wave. Add in a capacitor as a filter and sketch the waveform. What happens to the waveform when you change the resistance of the load? Again make sure that the DC current does not exceed half an amp. Repeat with additional capacitors. Use the scope to measure the peak-to-peak sawtooth amplitude $2A$ and simultaneously measure $(V_{AC})_{rms}$. Do you get the expected relationship?

Using both 680 μF capacitors, measure V_{AC} and V_{DC} as a function of I_{DC} by varying the load resistance. Collect about 15 data points. From these values plot (including errors) V_{AC} *vs.* I_{DC} and V_{DC} *vs.* I_{DC} using a program such as *WAPP*. From the slope of your V_{DC} *vs.* I_{DC} curve, calculate the internal resistance and the effective capacitance of the capacitors. Compare the calculated effective capacitance to the capacitance obtained from the component values. Do not be surprised if your values substantially disagree: the value printed on the capacitor may be off by more than 50%. Again calculate the effective capacitance from the slope of your V_{AC} *vs.* I_{DC} curve. Comment on the results.

2.3 Full-Wave Bridge Rectifier with π-Filter

Using the same two capacitors, construct a π-filtered power supply. Sketch the scope trace of the output voltage. Be sure to adjust the output current and scope scales so that the shape of the ripple is clearly visible. Compare this power supply to the previous RC-filter power supply in terms of ripple factor and regulation. (You must use the same current to make a fair comparison!)

3 Analysis of Data

Study your results and then discuss the advantages and disadvantages of the different types of power supplies based on your results. Include comparisons on the relative ease of reducing

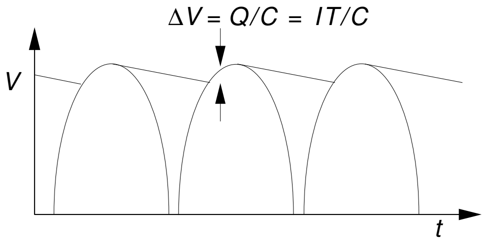

Figure 8: Filtered rectifier signal.

ripple and regulation as well as cost effectiveness.

4 Theory

Figure 8 is a graph of a filtered rectifier signal. We need to calculate the RMS value of the AC voltage. This can be done by making the approximation that the waveform is a sawtooth wave as in Figure 9. This is equivalent to saying that $T_1 \ll T_2$ or that the rise time is very small. Then:

$$(V_{AC})^2_{rms} = \langle V^2 \rangle = \frac{1}{T}\int_{-T/2}^{T/2}\left[-A\left(\frac{t}{T/2}\right)\right]^2 dt$$

where A is the *peak* AC voltage.

After integration

$$(V_{AC})^2_{rms} = A^2\,\frac{4}{T^3}\left[\frac{t^3}{3}\right]_{-T/2}^{T/2} = \frac{1}{3}\,A^2$$

or

$$(V_{AC})_{rms} = \frac{1}{\sqrt{3}}\,A$$

This expression was derived for a sawtooth wave, but it also holds true for any triangular wave.

When the capacitor is discharging we can write an expression for the voltage as follows:

$$V(t) = V_P\,\exp\!\left(-\frac{t}{RC}\right) \approx V_P\left(1-\frac{t}{RC}\right)$$

Again making the small rise time approximation, $T_1 \ll T_2$, we can say that when

$$t = T/2 = \frac{1}{2f}$$

then

$$\begin{aligned} V(t=T/2) &\approx V_P - A \\ &\approx V_P - V_P\,\frac{1}{2fRC} \end{aligned}$$

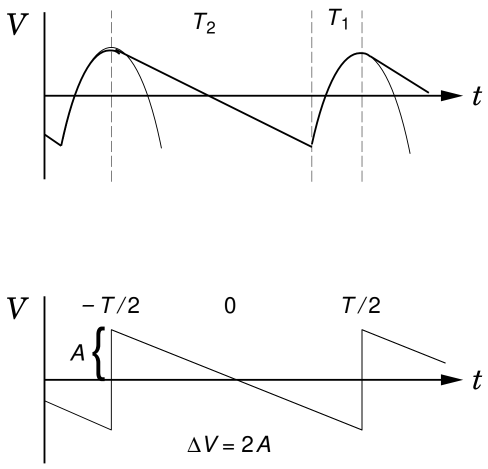

Figure 9: Sawtooth approximation.

so

$$A \approx V_P \, \frac{1}{2fRC}$$

On the right hand side we substitute the approximation that $V_P/R \approx I_{DC}$. Then

$$A \approx \frac{1}{2fC} \, I_{DC}$$

or

$$(V_{AC})_{rms} \approx \frac{1}{2\sqrt{3}\, fC} \, I_{DC}$$

Therefore

$$r = \frac{(V_{AC})_{rms}}{V_{DC}} = \frac{1}{2\sqrt{3}\, fR_{min}C}$$

We can also write

$$V_{DC} = V_P - A$$

where again A is the peak AC voltage. We showed earlier that

$$A \approx V_P \, \frac{1}{2fRC}$$

so

$$V_{DC} \approx V_P - \frac{V_P}{R} \, \frac{1}{2fC} \approx V_P - \frac{1}{2fC} \, I_{DC}$$

5 Notes on Using *WAPP* and the Web

The fitting and plotting for this lab can all be done via the web. Start your favorite web-browser. (I use *Netscape*.) Enter the web address:

`http://www.physics.csbsju.edu/`

Select Statistics. *WAPP*: Fit to data with y-errors is prepared to handle cases where the x-error is "small"; you should also find the option:
Fit to data with errors in both coordinates.

You should produce a plots (to appear in your notebook). Plots will be best reproduced on postscript printers. Select the "PDF" format; the program *Acrobat* should launch and allow you to see and print the plot.