Introduction

In almost all types of DC power supplies, a rectifier circuit and a filter capacitor are used to convert an AC voltage to a nearly constant DC voltage. Because electronic circuits are typically designed to be powered by DC sources, rectifier circuits are found in most equipment that operates from 60-Hz AC outlets. In practice, sophisticated voltage regulation circuits are usually employed to maintain DC supply voltages at specified levels; however, the simple circuit that you will study in this lab exercise forms the foundation of most commercial DC power supplies. In fact, this basic circuit, with a few minor modifications, is sufficient for many applications in which a small amount of power supply “ripple” (noise) can be tolerated. An example that will be explored in this lab exercise is providing power to an array of light-emitting diodes (LEDs).

Theoretical Background

A very basic power supply circuit is shown in Figure 1. A source of AC, typically 120 V rms and represented here by $v_{in}$, drives a transformer that might step up or step down the voltage. The transformer’s secondary voltage, represented by $v_{sec}$ in Figure 1, is therefore AC as well. If no load resistor $R_L$ is present (i.e., the load is an open circuit), the capacitor charges during the first half-cycle that the diode is forward biased, that is, during the portion of the first positive half-cycle of $v_{sec}$ for which $v_{sec} > V_F$, where $V_F$ is the turn-on voltage of the diode. The capacitor voltage ($v_o$ in Figure 1) during this time essentially equals $v_{sec}$ minus the voltage drop across the diode because the internal resistance $R_{sec}$ of the secondary winding and the diode resistance $r_d$ are negligibly small, and the time constant $(R_{sec} + r_d)C$ is much less than the period of the sinusoidal voltage waveform. If the load resistance $R_L$ is finite, then the time constant is $[R_L||(R_{sec} + r_d)]C$. (Do you know why?)

![Figure 1. Basic power supply circuit using half-wave rectifier.](image)

During the next half-cycle when $v_{sec}$ is negative, the capacitor remains charged because the diode is reverse biased, and there is no path available through which charge can leave the capacitor if $R_L$ is an open circuit. The diode is also off (non-conducting) during the subsequent positive half-cycles because the capacitor remains charged at a value near the peak positive secondary voltage; that is, $v_o \geq v_{sec} - V_F$, which leads to the condition $v_D \leq V_F$. If $R_L$ is infinite, the capacitor retains its charge and the voltage across it stays constant thereafter because the diode remains off at all times. No additional current can flow into the capacitor, but no current can flow out either (again, assuming the load is an open circuit). The voltage across the capacitor remains at the
peak positive value of the voltage across the secondary winding minus the value of the diode’s turn-on voltage.

Of course, a load must be connected to the circuit if it is to serve any useful purpose. In the case of a finite load resistance $R_L$, $v_o$ is not constant because the capacitor discharges though the load whenever $v_{sec}$ falls below the level necessary to keep the diode forward-biased. The circuit is therefore called a half-wave rectifier because it allows current to flow in only one direction though the load (“rectifier”), but current flows through the diode during only one of the two half-cycles (“half-wave”). Although the load current $i_L$ is unidirectional, its value nevertheless fluctuates as the capacitor voltage rises and falls.

The fact that the diode conducts during only one of the AC voltage’s half-cycles is a major disadvantage of the half-wave rectifier circuit. As shown in Figure 2, during the half-cycle when the diode does not conduct the capacitor continues to discharge through the load. During this time the capacitor and load resistor are effectively isolated from the rest of the power supply circuit, and the capacitor voltage drops exponentially with the time constant $R_L C$. If $R_L$ is relatively small, the current flowing out of the capacitor when the diode is off will be significant. As a result, the voltage across the capacitor can drop to an intolerably low level. The smaller the value of $R_L$, the smaller the time constant, and therefore the more quickly the capacitor discharges.

**Figure 2.** Ripple voltage in the output of a DC power supply with a filtered half-wave rectifier. The period $T$ is the reciprocal of the AC frequency $f$. The peak voltage $V_P$ is equal to the peak secondary voltage minus one diode drop.

The alternating charge and discharge cycles cause the output voltage of the power supply to fluctuate between a minimum value $V_{min}$ and a maximum value $V_{max}$, resulting in what is called a ripple voltage $V_r$ that is superimposed on the average DC output voltage. Since most loads require a nearly steady supply of DC, the presence of a significant ripple voltage is undesirable. The ripple voltage is sometimes expressed as a percentage and is calculated using the formula [1]

$$\% \text{ ripple} = 100 \frac{\text{peak-to-peak ripple voltage}}{\text{average DC voltage}}.$$
Since the average voltage might not be easy to predict, the percentage ripple is often approximated using
\[
\text{% ripple} \approx 100 \frac{\text{peak - to - peak ripple voltage}}{\text{peak DC voltage}} = 100 \frac{V_r}{V_p}. 
\]

The capacitor shown in Figure 1 is often called a filter capacitor because its purpose is to reduce the ripple voltage to an acceptable level.

The presence of ripple in the output of a power supply can be mitigated partly by using a full-wave rectifier circuit like the one shown in Figure 3. In this circuit, diodes \( D_2 \) and \( D_4 \) conduct during part of the positive half-cycles of \( v_{sec} \), and diodes \( D_1 \) and \( D_3 \) conduct during part of the negative half-cycles. During both half-cycles current flows downward through the load resistor. As with the half-wave rectifier, the diodes conduct for only a small part of each half-cycle because the slowly falling voltage \( v_o \) across the filter capacitor \( C \) ensures that the diodes are off \((v_D < V_F)\) most of the time.

![Diagram of full-wave bridge rectifier circuit with filter capacitor.](image)

As shown in Figure 4 on the next page, the full-wave rectifier is an improvement over the half-wave circuit because the capacitor is charged during part of both half-cycles. Consequently, the capacitor does not have as much time to discharge, and the output voltage does not drop as far as with the half-wave rectifier. For a given target ripple voltage only about half the filter capacitance is needed relative to that required in the half-wave rectifier. The only disadvantages of the full-wave circuit are the increased cost, weight, and space required for four diodes (this often turns out not to be significant) and the larger \( 2V_F \) voltage drop between the secondary voltage peak and the load voltage \( v_o \).

It should be clear by now that the selection of an appropriate value for the filter capacitor is an important design consideration. Fortunately, the value of \( C \) required for a given ripple voltage specification is easily determined. The current \( i_c \) that flows into the upper end of the filter capacitor in Figure 3 is related to the capacitor’s voltage (which is equal to \( v_o \)) by

\[
i_c = C \frac{dv_o}{dt}.
\]

If the ripple is a small percentage of the total output voltage, then the voltage across the capacitor decays almost linearly. (See Figure 4 or, for a more accurate depiction, Figure 4.25b in the
textbook [2].) As shown in Figure 4, $V_{\text{max}}$ is the maximum value of the output voltage, and $V_{\text{min}}$ is the minimum value. If the ripple is small, then the capacitor will not start charging again until almost the next time the secondary voltage reaches a peak (represented by $|v_{\text{sec}}|_{pk}$). For a full-wave rectifier, the next voltage peak occurs one half-period ($0.5T$, where $T$ is the period) later. The time derivative of the output voltage during the half-cycle can therefore be approximated as

$$\frac{dv_o}{dt} \approx \frac{V_{\text{max}} - V_{\text{min}}}{0.5T},$$

where the negative sign indicates that the output voltage falls as the capacitor discharges (negative slope). Substituting this result into the $i$-$v$ relationship for the capacitor yields

$$i_c = C \frac{dv_o}{dt} \approx -C \frac{V_{\text{max}} - V_{\text{min}}}{0.5T}.$$

![Diagram of ripple voltage in the output of a DC power supply with a full-wave rectifier.](image)

**Figure 4.** Ripple voltage in the output of a DC power supply with a full-wave rectifier. The period $T$ is the reciprocal of the AC frequency $f$. The filter capacitor discharges for only half a period before it is recharged to the peak voltage $V_P$. The output voltage therefore drops only half as far as that in a half-wave rectifier for the same $C$ and $R_L$ values. The peak voltage $V_P$ is equal to the peak secondary voltage magnitude minus two diode drops.

The diodes are off when the capacitor discharges, so the only place the capacitor current can flow is through the load resistor. Since $i_c$ is defined as flowing into the upper end of the capacitor, this means that $i_c = -i_L$ when the capacitor discharges. If the ripple in the output voltage is a small fraction of the peak output voltage, then the output voltage will be near its peak value $V_P$ over the whole half-cycle, and the load current can therefore be approximated as

$$i_L \approx \frac{V_P}{R_L}.$$
Substituting this result into the expression for $i_c$ above leads to the relationship

$$\frac{V_p}{R_L} \approx i_L = -i_c = C \frac{V_{\text{max}} - V_{\text{min}}}{0.5T}.$$

The ripple voltage $V_r$ is defined as the extent of the fluctuation of the output voltage, so $V_r = V_{\text{max}} - V_{\text{min}}$. Thus,

$$\frac{V_p}{R_L} \approx C \frac{V_r}{0.5T}.$$

This can be rearranged as

$$\frac{V_r}{V_p} \approx \frac{0.5T}{R_L C} = \frac{T}{2R_L C}.$$

The left-hand side is the “fractional” ripple; that is, it is the ripple amplitude expressed as a fraction of the peak output voltage. For example, if the percentage ripple is 5%, then the fractional ripple is 0.05. The frequency $f$ of the AC voltage is typically known, and the load resistance is either also known or can be estimated to a fair degree of accuracy. If the load is variable, then the most demanding load (i.e., the condition under which the most current will be drawn, which corresponds to the minimum likely value of $R_L$) is used in the equation. The minimum required filter capacitance to meet a given ripple specification can be found by solving the equation above for $C$; the result is

$$C = \frac{T}{2R_{L_{\text{min}}}} \frac{1}{(V_r/V_p)} = \frac{1}{2f R_{L_{\text{min}}}} \left( \frac{1}{V_r/V_p} \right),$$

where the relationship $f = 1/T$ has been used. More typically, the maximum required output current is specified. In that case, the relationship $i_{L_{\text{max}}} = V_p/R_{L_{\text{min}}}$ can be substituted to obtain a more useful expression for $C$.

The output voltage of the simple DC power supply discussed here is approximately two diode voltage drops (1.4-2.0 V) below the peak magnitude of the secondary voltage ($|v_{\text{sec}}|$). If a particular output voltage level is required for a given application, then a transformer must be selected that has the appropriate peak secondary voltage rating. This can be a significant limitation, since not many secondary voltage options are available. Later in the course we will study methods for obtaining any desired output voltage level that lies below the secondary voltage peak.

References

Experimental Procedure

STOP! Before proceeding, please read and understand the following two very important warnings. If they are not clear to you, please discuss them with your instructor or TA.

Warning #1: Do not attempt to measure both the AC voltage on the secondary winding of the transformer ($v_{sec}$) and the output voltage across the load resistor ($v_o$) with the oscilloscope at the same time. The ground leads would create a short across diode $D_1$ in Figure 3 that would likely lead to the destruction of diode $D_1$. You should trace the circuit connections in Figure 3 and understand how this can happen before proceeding.

Warning #2: Electrolytic capacitors are polarized. Failure to pay attention to their polarity could result in their spectacular destruction and a trip to the hospital or at least an unpleasant smell for everyone nearby. The marking on an electrolytic capacitor’s package usually indicates its negative terminal.

- Design and assemble a DC power supply with a full-wave bridge rectifier like the one shown in Figure 5 on the next page. This circuit is identical to the one shown in Figure 3, except that a load consisting of three LEDs wired in parallel has been added. A transformer will be supplied to you. For safety reasons, it is enclosed in a box with a power cord and a circuit breaker. As shown in Figure 6 on the next page, there are three jacks on the box that are connected to the secondary winding. The two red jacks connect to the ends of the secondary winding, and the green jack connects to a center tap. For this lab experiment, take the AC voltage for your power supply between the center jack and one end jack. Before you can design your circuit, you will need to determine the secondary voltage of the transformer by measurement.

The power supply should have the following specifications:

- Diode type: 1N4001 or 1N4007 (see data sheet)
- Avg. DC output voltage: whatever is available from the transformer, minus two diode drops
- Max. expected load current: enough to produce a luminous intensity of 3 mcd from each LED (see data sheet)
- Max. percentage ripple: 5%

Note 1: Think carefully about how you determine a value for the equivalent load resistance. Remember that the LEDs are modeled as independent voltage sources, and they are in series with the current-limiting resistors $R_B$. You might prefer to use some of the ideas given in the “Theoretical Background” section to derive a more useful design formula for $C$.

Note 2: The value of the current-limiting resistors $R_B$ needs to be determined as well. They should be chosen so that each LED produces a luminous intensity of 3 mcd at the output voltage of the power supply.

Note 3: You might need to use a value for the filter capacitor that exceeds any single value available in the parts bins. You may combine capacitors in series and/or parallel to achieve the desired capacitance, but use good design practice and avoid overdoing it. Keep in mind
that the tolerance of electrolytic capacitors is typically 20-40% and that electrolytic capacitors are bulky and relatively expensive. Your filter capacitor network (and its complexity) should be consistent with that tolerance range. A design that uses an excessive number of capacitors in an effort to achieve an exact value will be viewed unfavorably!

- **Before applying power**, check the power dissipation levels of all resistors and ensure that they are being used within their ratings. If any are not, redesign your circuit so that no ratings are being exceeded.

**Figure 5.** Full-wave bridge rectifier circuit with filter capacitor and three-LED load. The LED bias resistors $R_B$ all have the same value. The “+” symbol next to the upper plate of the capacitor indicates that it is an electrolytic type. Electrolytic capacitors are commonly used in power supply circuits because they are available in large values. They are also polarized; that is, the voltage across them must have the indicated polarity for proper operation.

**Figure 6.** Connections to transformer inside transformer box.

- Display the output voltage waveform on the oscilloscope, and check whether or not your power supply meets the specifications. Troubleshoot any problems. Once you are confident that the power supply is working properly, demonstrate it to the instructor or TA.

- Display the following three waveforms on the oscilloscope one at a time, and capture each screen image to include in your summary:
  1. AC voltage waveform across the secondary winding. **Heed the warning above!**
  2. Output voltage waveform at maximum output current *without* the filter capacitor in place.
  3. Output voltage waveform at maximum output current *with* the filter capacitor in place.
Note: For the third case, the ripple voltage might be so low that you will have to adjust the oscilloscope’s trigger controls to stabilize the displayed waveform. If that does not work, then you might have to switch to a more sensitive vertical scale and move the 0-V level off the screen. You can determine the peak output voltage and ripple voltage using the manual cursors.

Lab Summary

After your group has completed the assigned tasks and demonstrated a working circuit, prepare a written summary no more than two pages long (not including the screen captures) that includes but is not necessarily limited to the following elements:

a. Description of all circuit design choices (including power dissipation calculations), assembly steps, and results of measurements with diagrams as appropriate.

b. The three screen captures (with appropriate annotations and captions) obtained in the last step of the “Experimental Procedure” section.

c. A comparison of the three screen captures. Point out the differences between them (some are obvious, but some are subtle), and relate your observations to what you know about how power supplies operate.

d. A comparison of the measured percentage ripple to the target value.

Note: Comparisons should consist of more than simply stating whether two items or values are similar or different. They should include discussions of the implications of the results and of outcomes that are unexpected or at least not obvious (e.g., how realistic design constraints affect your ability to meet specifications). Point out ideas, relationships, impacts, implications, etc. that the reader might miss without your guidance.

The summary should be thorough, clear, concise, and professional in tone and style. It does not have to be word-processed, but it should be easy to follow and as neat and well organized as possible. If it is word-processed, the font should be 11 points or larger, and the margins should be at least one inch wide. Single line spacing is acceptable. Equations, diagrams, and tables may be generated by hand, or you may use software. Because this summary will include several oscilloscope screen shots, you should pay especially close attention to the relevant sections of the “Lab Report Guidelines.”

You may use memo format for your summary if you wish, but you do not have to. A cover sheet is not necessary. The identifying information on the first page should include the group members’ names, the course number (ELEC 350), the lab section (Monday or Wednesday), the lab number, and the lab date (not the summary due date).
Grading

Each group member will receive the same grade based on the following criteria. Scores will be quantized at the indicated percentage levels.

0, 15, 30, 45, 60%  Demonstration of fully operational circuit that meets specifications
0, 5, 10, 15, 20%  Summary – Completeness and technical accuracy
0, 5, 10%  Summary – Organization, neatness, and style (professionalism)
0, 5, 10%  Summary – Spelling, grammar, and punctuation

As outlined in the lab policies and guidelines, any group member who misses any portion of the lab session and is not excused will receive a grade penalty proportional to the time absent.

If the demonstration is not completed by the end of the lab session, full demonstration credit can be obtained if the circuit is made to operate and a detailed one-page (or less) explanation of the problem and its solution is provided within 24 hours. The explanation is separate from the lab summary.

The lab summary is due at the beginning of next week’s lab session. Summaries submitted after the deadline but before 6 pm on the following day will result in a 20% grade deduction applied to the lab grade. No credit will be given for a summary submitted later, although credit for successful demonstration of the assigned circuit will still be given.

Group Assignments

The randomly generated groups for this lab exercise are listed below:

Monday section
Kaspar-Hontz
Brown-Hough
Ludwig-Gegg
DAbraccio-Rocci
MacGibbon-Daughan-Goesseringer

Wednesday section
Opalinski-Ononuju
Breen-Bekampis
Kwiatkowski-Clark
Mylet-Moore
Carno-Bacon
Bennett-Sommers

© 2001-2013 David F. Kelley, Bucknell University, Lewisburg, PA 17837.