Lab #7: Voltage Regulation Using a Zener Diode

Introduction

Simple DC power supplies that consist only of a transformer, full-wave rectifier, and filter capacitor are adequate for many practical applications. However, this basic circuit has several important disadvantages: 1) the capacitors required to reduce the ripple voltage to a small magnitude are physically large and expensive; 2) even with minimal ripple, the output voltage can vary considerably due to AC line voltage fluctuations; 3) the secondary winding of the transformer must be selected or designed to provide the desired output voltage; and 4) changes in load current can lead to changes in output voltage due to the voltage drops across the internal resistances of the rectifier diodes and transformer windings. These deficiencies can be addressed through the use of a voltage regulator circuit, which maintains the output voltage of the power supply close to a predetermined level regardless of component and load variations. Zener diodes, which exhibit very stable voltages across themselves when operated in the reverse breakdown region, can serve as simple yet effective voltage regulators in a wide range of applications. In this lab exercise you will design one such circuit.

Pre-Lab Work

Read over the “Theoretical Background” and “Experimental Procedure” sections of this handout carefully, and then determine the required value of resistor $R_s$ in Figure 2 to meet the specifications given in the “Experimental Procedure” section. At the beginning of the lab session, submit a written summary of the design process you followed (including equations with the substituted numerical values shown) to determine the resistor’s value. Your summary may be handwritten on loose-leaf paper. It will not be graded for style, formatting, spelling, and grammar; however, it must be legible and easy to follow.

Theoretical Background

All diodes exhibit reverse breakdown behavior when subjected to a reverse-bias voltage of sufficiently high magnitude. Reverse breakdown is not necessarily destructive, though. While it is normally associated with ratings being exceeded in standard pn-junction diodes, zener diodes, by contrast, are designed to operate in this mode safely. As shown in the $i$-$v$ characteristic in Figure 1, the reverse breakdown region is marked by the zener voltage, $V_Z$. A zener diode behaves like a standard pn-junction diode in the reverse-bias and forward-bias regions because the $i$-$v$ characteristic obeys the familiar diode equation for $v_D > -V_Z$. However, for $v_D < -V_Z$, where the diode operates in the reverse breakdown region, the slope of the $i$-$v$ curve is much steeper than it is in the forward-bias region. This implies that the voltage across the diode remains very close to $-V_Z$ in reverse-breakdown mode, regardless of the level of diode current. It is this characteristic that makes the zener diode useful as a voltage regulator. If a load is connected in parallel with a diode operating in reverse breakdown mode, then the voltage across the diode, and therefore the voltage across the load, will remain very close to the zener voltage.
Figure 1. Zener diode $i$-$v$ characteristic.

A typical power supply circuit that employs a zener diode as a voltage regulator is shown in Figure 2. The circuit has a filter capacitor, but its value does not have to be as large as one in an unregulated supply because the zener diode effectively smoothes out most of the ripple.

Figure 2. Full-wave bridge rectifier circuit with filter capacitor and zener diode voltage regulator. Resistor $R_b$ is a “bleeder” resistor that ensures capacitor $C$ quickly discharges when the power is shut off, even if the load is an open circuit.

The design procedure for this type of circuit differs from that used for the basic full-wave circuit. Most regulated power supplies are designed to provide a constant output voltage for a wide range of load currents up to some maximum value. The output voltage is equal to the zener voltage, so the output voltage specification dictates the value of $V_Z$. The next component value to be set is usually the peak voltage of the secondary winding of the transformer. One commonly used rule of thumb is to set the voltage to a value approximately 30-50% (or more) higher than the desired output voltage. Recall that the voltage across the filter capacitor approximately equals the peak voltage of the secondary minus two diode voltage drops. The 30-50% rule of thumb helps to ensure that there is enough voltage “headroom” between the output voltage of the rectifier/filter capacitor circuit (labeled $v_C$ in Figure 2) and the zener voltage. This buffer is necessary to ensure that sufficient current flows through the zener diode to keep it in the reverse-breakdown region even at maximum load current, in spite of component variations and possible fluctuations in the
AC line voltage. [Note: In this lab exercise, the secondary voltage is dictated by the lone transformer type that is available.]

Recall that during most of the AC cycle the four rectifier diodes are off. Thus, most of the time the capacitor is supplying the current $i_S$ that is shared between the zener diode and the load. By KCL,

$$i_S = i_Z + i_L.$$

We also note that

$$i_S = \frac{v_C - V_Z}{R_S},$$

where $v_C$ is the voltage across the capacitor, and $V_Z$ (which equals $v_o$) is the zener voltage. The capacitor voltage must be maintained above $V_Z$ to ensure that the load receives sufficient current for its needs and that the zener diode conducts at least a minimum amount of current at all times in order to remain in the reverse breakdown region. As shown in Figure 3 below, the capacitor voltage $v_C$ has some ripple, which means that $i_S$ will vary as well. If $v_C$ is allowed to drop to a value close to $V_Z$ (i.e., if the ripple is very large), then $R_S$ will have to be very small in order to allow sufficient current $i_S$ to flow into the zener diode and the load at those instances. However, if $R_S$ is too small, then at the peaks of $v_C$ (at $V_{\max}$) an excessive amount of current would flow through the zener diode. This is because the load draws a relatively constant current $i_L$, at least over time scales of several periods $T$ or more. Thus, if $i_S$ were to increase and $i_L$ remain constant, then the zener diode would have to pass the excess current $i_Z$. There are conflicting trade-offs here. On the one hand, a small $C$ value (resulting in large ripple) is desirable because a small capacitor would be cheaper, smaller, and lighter than a large one. On the other hand, a large $C$ value (small ripple) puts less stress on the zener diode by limiting the variations in the value of $i_S$. However, the use of a large capacitor also places more stress on the rectifier diodes and transformer because the peak rectifier diode current is high if the ripple is small.

![Figure 3](image-url)

**Figure 3.** Ripple voltage across the filter capacitor in a DC power supply with a full-wave rectifier and zener diode voltage regulator. The peak voltage $V_{\max}$ is equal to the peak secondary voltage of the transformer minus two diode drops. A typical rule of thumb is to set the ripple voltage $V_r$ to be about $1/5$ the difference between $V_{\max}$ and $V_Z$. The period $T$ is the reciprocal of the AC frequency $f$.  

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Over time, a rule of thumb has emerged to resolve this trade-off. Designers typically select a capacitor that sets the ripple voltage to a value that is 20% of the difference between the peak voltage $V_{\text{max}}$ and the zener voltage $V_Z$. That is, $V_r = 0.2(V_{\text{max}} - V_Z)$. The selection of the capacitor will be discussed in more detail later.

As mentioned earlier, the zener current $i_z$ has to be maintained above a certain level to ensure that the diode operates in the reverse-breakdown region. Another commonly used rule of thumb is that the minimum zener current should be approximately 1/20 of the diode’s maximum safe operating current. The latter is not usually specified directly on data sheets, but it can be determined from the maximum safe power dissipation rating $P_{Z\text{rated}}$, which is almost always provided.

The value of $i_s$ must be high enough to supply $i_{L\text{max}}$ and $i_{Z\text{min}}$ at the same time, even when $v_C = V_{\text{min}}$. We therefore need to make sure that

$$i_{S\min} = i_{Z\min} + i_{L\text{max}}.$$

Since

$$i_s = \frac{V_C - V_Z}{R_S},$$

the maximum value of the current-limiting resistor $R_S$ is given by

$$i_{S\min} = \frac{V_{\text{min}} - V_Z}{R_{S\text{max}}} \rightarrow R_{S\text{max}} = \frac{V_{\text{min}} - V_Z}{i_{S\min}} \rightarrow R_{S\max} = \frac{V_{\text{min}} - V_Z}{i_{Z\min} + i_{L\text{max}}}. $$

Using $V_{\text{min}} = V_{\text{max}} - V_r$ and $V_r = 0.2(V_{\text{max}} - V_Z)$, this becomes

$$R_{S\max} = \frac{V_{\text{max}} - V_r - V_Z}{i_{Z\min} + i_{L\text{max}}} = \frac{V_{\text{max}} - 0.2(V_{\text{max}} - V_Z) - V_Z}{i_{Z\min} + i_{L\text{max}}} \rightarrow R_{S\max} = \frac{0.8(V_{\text{max}} - V_Z)}{i_{Z\min} + i_{L\text{max}}}. $$

This sets an upper limit on the value of $R_S$, but the resistance cannot be arbitrarily small. When $i_L$ is zero, all of $i_s$ flows through the zener diode. To ensure that the maximum safe zener current is not exceeded under no-load conditions when $v_C$ is at its peak, $R_S$ must have a minimum value given by

$$R_{S\min} = \frac{V_{\text{max}} - V_Z}{i_{Z\text{max}}},$$

where $i_{Z\text{max}}$ is typically half or so of the maximum rated current.

Finally, the required value for the filter capacitor $C$ can be calculated. When all four rectifier diodes are reverse biased and the capacitor is discharging, we can make the approximation that $i_s$ is close to its peak value at all times. Thus,

$$i_s = -C \frac{dv_C}{dt} \approx C \frac{V_{\text{max}} - V_{\text{min}}}{0.5T} = 2Cf(V_{\text{max}} - V_{\text{min}}) = 2CfV_r,$$
where \( T \) and \( f \) are the period and frequency, respectively, of the AC voltage driving the circuit (\( T = 16.7 \) ms and \( f = 60 \) Hz in the case of commercial power in the United States). Substituting for \( V_r \) the relationship \( V_r = 0.2(V_{\text{max}} - V_Z) \) in the expression for \( i_S \) above leads to
\[
i_S = 2CfV_r = 2Cf(0.2)(V_{\text{max}} - V_Z) = 0.4Cf(V_{\text{max}} - V_Z),
\]
from which we obtain
\[
C_{\text{min}} = \frac{i_S}{0.4f(V_{\text{max}} - V_Z)}.
\]

A conservative approach is to set \( i_S \) to its maximum possible value in the formula. The capacitor value actually used should be the next standard value above the calculated minimum value.

Experimental Procedure

**Warning #1:** Do not attempt to measure both \( v_{sec} \) and \( v_o \) in Figure 2 with the oscilloscope at the same time. The ground leads could create a short between two circuit nodes that could destroy one or more components. You should inspect Figure 2 and understand how this can happen before proceeding.

**Warning #2:** Electrolytic capacitors are polarized. The marking on an electrolytic capacitor’s package usually indicates its negative terminal. Look for a thick “−” sign.

- Design a regulated power supply like the one shown in Figure 2 using one of the supplied transformer boxes. The power supply should meet the following specifications:

  DC output voltage: approximately 9 V
  Maximum load current: 50 mA
  “Bleeder” resistance \( R_b \): should discharge the capacitor to 5% of its maximum voltage within 2-3 seconds when the power supply is turned off; it should not load down the rectifier significantly when the power supply is on (i.e., it should not add significantly to \( i_Z + i_L \)).

Recommendations and hints:

1. Check the peak voltage of the transformer’s secondary (end-to-end and center-to-end).
2. The capacitor will discharge to the zener voltage \( V_Z \) quickly even without the bleeder resistor \( R_b \) in place. (Do you know why?) Select the value of \( R_b \) to discharge \( C \) the rest of the way to zero volts within a few seconds.
3. Measure or look up the turn-on voltage of the rectifier diodes you use. Consult the appropriate plot in the data sheet. Data sheets for standard and zener diodes are available via a link on the Laboratory web page.
4. Determine the expected dissipated power of all resistors and diodes (including \( R_L \)), and modify the design if necessary to avoid exceeding device ratings. It might be necessary to estimate the average values of the currents \( i_S \) and/or \( i_Z \); make sure your estimates are reasonable for the worst cases expected. Apply a \( \times 2 \) safety factor.
5. Electrolytic capacitors may be combined in series and/or parallel if capacitors of the desired standard value are not available. However, keep in mind the tolerances of the capacitors and the imprecision of the various rules of thumb employed in the design. Do not waste money by overdesigning.

• Devise a way to test whether or not your power supply is working correctly at full rated output current. Once you are confident that it is, demonstrate your working circuit to the instructor or TA.

• With the power supply delivering its maximum rated load current, capture a screen image of the output waveform $v_o$ and the capacitor voltage $v_C$ being simultaneously displayed. Also, calculate the percentage ripple of the output voltage waveform. You might need to change the oscilloscope’s settings for the latter task in order to observe the tiny ripple voltage.

• Measure and record the DC output voltage obtained when the supply provides the maximum rated load current, half of the maximum load current, and no load current. Use the bench-top voltmeter in order to obtain measurements with several digits of accuracy. The three measured values should be slightly different. Explain your observations qualitatively in terms of the piecewise linear model for a zener diode operating in the reverse-breakdown region.

• Answer the following question in your report: What capacitor value would you have had to use in an unregulated power supply with a full-wave rectifier in order to obtain the same ripple as observed here at maximum rated load current? Compare the result to the capacitor value you used in the regulated supply, and comment.

Grading

Each group must submit a brief but well written report that describes in detail all circuit design choices, assembly steps, and the results of measurements. The report should include (but not necessarily be limited to) all of the details requested in the “Experimental Procedure” section. Because this report will include several oscilloscope screen shots, you should pay especially close attention to the relevant sections of the “Lab Report Guidelines.” Be sure to include a brief discussion of the extent to which your circuit met the specifications (not just the “what” but also the implications). Also include the output voltage measurements for the three specified loads and your explanation of the observed variations.

The report is due at the beginning of the next lab session. Each group member will receive the same grade, which will be determined as follows:

20% Pre-lab work: determination of the value of $R_s$
30% Demonstration of properly operating power supply
30% Report – Completeness and technical accuracy
10% Report – Organization, neatness, and style (professionalism)
10% Report – Spelling, grammar, and punctuation

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