

CIRCUITS LABORATORY

Experiment 8

DC Power Supplies

8.1 INTRODUCTION

This exercise constitutes a study of circuits that approximate an ideal constant-voltage source. Recall that the ideal constant-voltage source has the property of maintaining a constant voltage regardless of the current through the supply; that is, it may be regarded as a Thevenin equivalent circuit with a resistance of zero. Any actual circuit is necessarily an approximation to an ideal source; to construct a source that is capable of supporting such a range of currents or voltage is impractical.

Students are cautioned that they will be dealing with currents and voltages that are potentially damaging to all components used in this exercise. The transformer power should always be turned off prior to altering the circuit and the transformer primary circuitry should never be altered. The ability of the components to withstand the currents and voltages to which they will be subjected should always be considered before their insertion into the circuit: a 1/4 Watt resistor subject to a current of 100 mA and a voltage of 40 V will not continue to be a reliable resistor for long. Also, observe the polarities of all components that are polarized and insert them into the circuits properly.

8.2 THE BASIC SUPPLY

The basic supply of voltage for the constant-voltage source illustrated in Figure 8.1 is the transformed line voltage. The transformer reduces the line voltage (a 60 Hz

sinusoidal voltage, approximately 120 V rms) to a voltage of approximately 28 V rms in this exercise. The 1/2 Amp RMS line fuse limits the transformer primary current to a value significantly smaller than that permitted by the 15 A RMS line circuit breaker.

In constructing a constant voltage supply, one must first convert the sinusoidal transformer secondary voltage to a voltage having a non-zero average value, that is, to produce a voltage with a non-zero DC component. This may be accomplished through the use of half-wave or full-wave rectification, illustrated in Figures 8.1(a) and 8.1(b), respectively. In half-wave rectification, a single diode or rectifier is used to block current during half of the voltage cycle. In full-wave rectification, a more sophisticated diode scheme, commonly called a full-wave bridge, is used to supply current during both the positive and negative half-cycles.

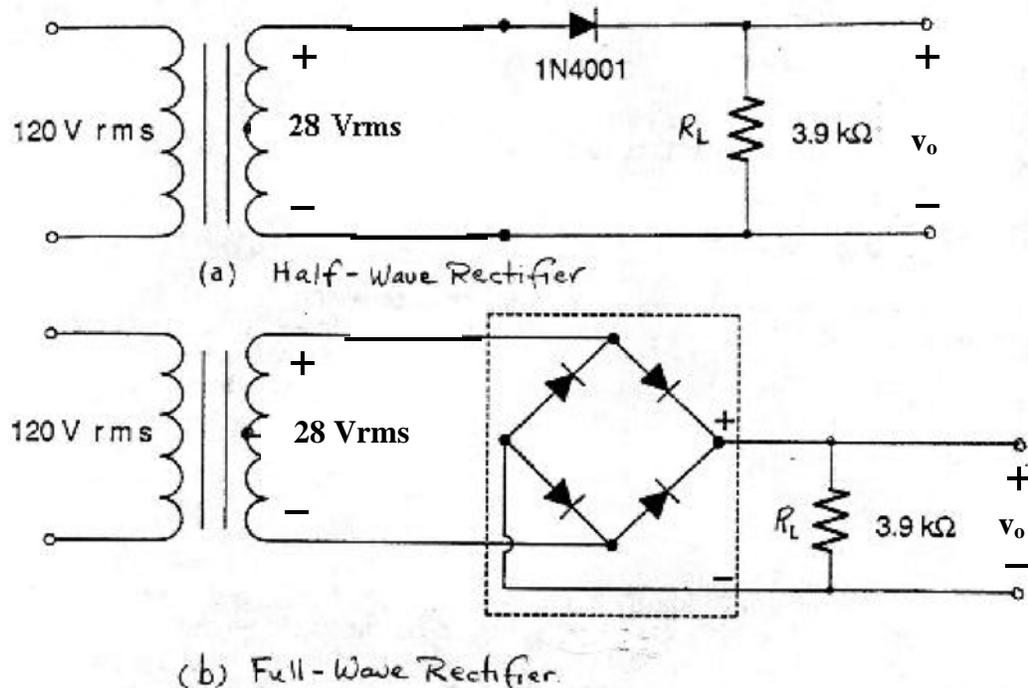


Figure 8.1: Rectifier Circuits

8.2.1 Half-Wave Rectifier

In order to understand the operation of the half-wave rectifier, consider the circuit shown in Figure 8.2. In this circuit, the transformer secondary output is represented as an ideal AC sinusoidal voltage source v_s with a magnitude of 28 V rms and a frequency of 60 Hz plus a source resistance R_s . It follows that if $v_s = V_m \sin\omega t$, then $V_m = 28\sqrt{2} = 39.6$ volts peak and $\omega = 2\pi(60) = 377$ radians/sec. The output of the voltage source is then connected in series with the 1N4001 diode and the 3.9 k Ω load resistor, R_L .

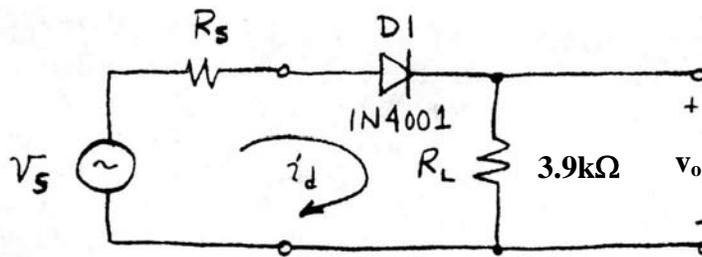


Figure 8.2: Half-wave rectifier circuit.

Using an *ideal model* for the diode, it follows that during the positive half cycle (i.e., when $v_s > 0$), the diode will be forward biased and a current i_d will be produced in the direction shown. Since the diode appears as a short circuit using the ideal model, the value of the current is determined by v_s , R_s and R_L . When v_s is negative, it acts to produce a current in the opposite direction but, since this is in the reverse direction of the diode, the diode operates as an open circuit and the current is zero. Neglecting diode drop, the waveform of the output voltage $v_o = R_L i_d$ is shown in Figure 8.3, and is given by:

$$v_o = \frac{R_L}{R_s + R_L} v_s \quad \text{for } v_s > 0 \quad (8.1)$$

$$v_o = 0 \quad \text{for } v_s \leq 0 \quad (8.2)$$

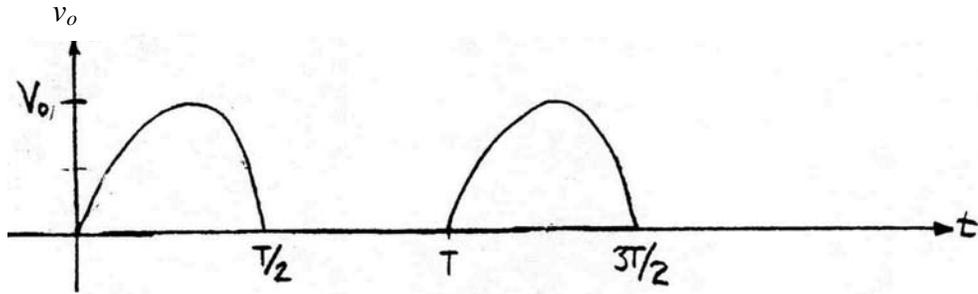


Figure 8.3: Output waveform of half-wave rectifier.

The output voltage across the load resistor is periodic; therefore it can be represented by a Fourier Series. If the peak instantaneous value of v_o is designated by V_o , then

$$v_o = V_o \left(\frac{1}{\pi} + \frac{1}{2} \sin \omega t - \frac{2}{3\pi} \cos 2\omega t - \frac{2}{15\pi} \cos 4\omega t + \dots \right) \quad (8.3)$$

Inspection of Eq. (8.3) shows that v_o consists of a DC component equal to V_o/π . Thus, the circuit has produced an output voltage that has a non-zero DC component from the sinusoidal transformer secondary voltage that has a zero DC component. This action of generating a direct voltage from an alternating supply voltage by a diode is called **rectification**. In addition, v_o consists of sinusoidal components at the fundamental radian frequency ω and at integer multiples of ω , called harmonics. Therefore, as a consequence of the nonlinearity of the diode, the voltage across the load resistor R_L contains components at frequencies not present in the voltage applied to the circuit. Recall that in circuits consisting entirely of linear elements (resistors, inductors and capacitors), only frequencies present in the applied voltages and currents can appear.

The rms value of the periodic output voltage, which can be obtained by directly integrating the square on the half-wave signal shown in Figure 8.8, is given by

$$V_{EFF} = V_o(rms) \cong \sqrt{\frac{1}{T} \int_0^{T/2} (V_o \sin \omega t)^2 dt} \quad (8.4)$$

from which it follows that

$$V_{EFF} = V_o(rms) = V_o/2 \quad (8.5)$$

From Equation (8.1), we see that if $R_s \ll R_L$, then

$$V_o(\text{peak}) = V_m \left(\frac{R_L}{R_L + R_s} \right) \cong V_m \quad (8.6)$$

from which it follows that:

$$V_o(\text{rms}) \cong V_m / 2. \quad (8.7)$$

In addition, the DC or average component of v_o can be estimated as:

$$V_o(\text{DC}) \cong V_m / \pi . \quad (8.8)$$

In the above analysis, an *ideal diode model* was used. Using a real diode, one must consider the specifications or maximum rating of the diode to ensure that these ratings are not exceeded. First, the forward bias voltage of the diode is $V_{D(\text{ON})} = 0.7 \text{ V}$ for a silicon diode rather than a short circuit for the ideal diode model. Assuming $V_m \gg V_{D(\text{ON})}$, then the above estimates remain valid.

In addition, an ideal diode can conduct any value of current in the forward direction, and it remains an open circuit for all values of inverse voltage. This is not the case, however, with physical diodes. In general, there is a limit to the peak instantaneous current, $i_{d(\text{max})}$, that can be passed without damage; and there is a limit to the peak instantaneous inverse voltage, $v_{D(\text{piv})}$, that can be applied. Therefore, one must ensure that these two quantities do not exceed the maximum permissible values in any design.

In the half-wave rectifier, when an inverse voltage exists across the diode, there is no voltage drop across the circuit resistances since the diode acts as an open circuit under this condition. In actuality, there is a small amount of reverse leakage current through the diode, but it can be ignored in this analysis. It follows that the peak inverse voltage is simply given by:

$$V_{D(\text{piv})} = V_m . \quad (8.9)$$

The instantaneous peak forward current occurs when v_s has its maximum positive value and the magnitude of this current is given by:

$$i_{d(\max)} = \frac{V_m}{R_s + R_L}, \quad (8.10)$$

where we have assumed $V_{D(\text{ON})} \ll V_m$. Further, if $R_s \ll R_L$, then :

$$i_{d(\max)} \cong \frac{V_m}{R_L}. \quad (8.11)$$

8.2.2 Full-Wave Rectifier

In order to understand the operation of the full-wave rectifier shown in Figure 8.1 (b), consider the circuit shown in Fig. 8.4. Again, the output of the transformer is represented by a sinusoidal voltage source v_s and source resistance R_s , but, as shown, it is connected to the load resistor R_L through a bridge rectifier consisting of four diodes.

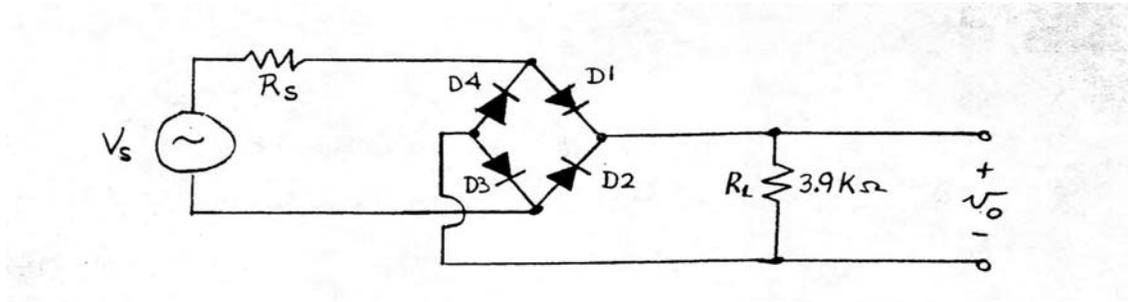


Figure 8.4: Full-wave rectifier circuit.

During the positive half cycle of v_s , D1 and D3 turn on and act as a short circuit while D2 and D4 turn off and act as an open circuit. Under this condition:

$$v_o = v_s - 2(V_{D(\text{ON})}) \cong v_s, \quad (8.12)$$

where we have assumed $2(V_{D(\text{ON})}) \ll V_m$ and that $R_s \ll R_L$. It follows that the peak voltage across R_L will be:

$$V_{o(\max)} \cong V_m - 2(V_{D(\text{ON})}) \cong V_m. \quad (8.13)$$

During the negative half cycle of v_s , D2 and D4 turn on and act as a short circuit while D1 and D3 turn off and act as an open circuit. Under this condition:

$$v_o \cong -v_s + 2(v_{D(\text{ON})}) \cong -v_s, \quad (8.14)$$

since the current through R_L is in the same direction as during the positive half cycle.

The resulting output voltage, v_o , is shown in Fig. 8.5 and can be expressed mathematically as :

$$v_o = |v_s| = |V_m \sin \omega t| . \quad (8.15)$$

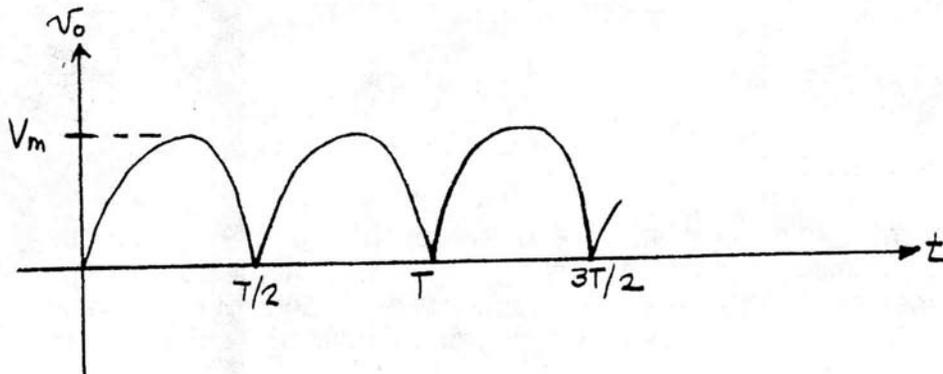


Figure 8.5: Output voltage for full-wave rectifier.

Again, since v_o is periodic, it can be expressed in the form of a Fourier series:

$$v_o = V_m \left(\frac{2}{\pi} - \frac{4}{3\pi} \cos 2\omega t - \frac{4}{15\pi} \cos 4\omega t - \dots \right) \quad (8.16)$$

Thus, the voltage across the load consists of a DC component of magnitude $2V_m/\pi$ and a set of sinusoidal components at frequencies that are even multiples of the frequency of v_s . It follows that the average value of the output voltage is given by :

$$V_o(\text{DC}) = 2V_m/\pi \quad (8.17)$$

and the effective (true rms) value can be shown to be

$$V_o(\text{rms}) \cong V_m / \sqrt{2} \quad (8.18)$$

Notice that one advantage of full-wave rectification is that the DC value of the output voltage for the full-wave rectifier is twice the DC value for the half-wave rectifier, i.e., $2V_m/\pi$ compared to V_m/π .

The peak inverse voltage across the diodes can be determined by noting that during the positive half-cycle of v_s , the voltage across D_1 is $V_{D(ON)}$ since it is forward biased. During the negative half-cycle, it is $-V_m \sin \omega t$ since D_1 is reverse biased and operates as an open circuit. So, it follows that:

$$V_{D1(piv)} = V_m \quad (8.19)$$

A similar analysis shows that the peak inverse voltage for all four diodes is the same, namely, V_m .

The peak current is given by:

$$I_{D(max)} = \frac{V_m - 2V_{D(ON)}}{R_L + R_s} \cong \frac{V_m}{R_L}, \quad (8.20)$$

where we have assumed that $2 V_{D(ON)} \ll V_m$ and $R_s \ll R_L$. From this, we see that with the bridge rectifier (4 diodes rather than 1), twice the DC voltage can be delivered to the load resistor, R_L , using diodes with the same instantaneous peak inverse voltage and maximum current rating.

8.2.3 Half-wave Rectifier with a Capacitor Filter

The half-wave rectifier discussed in Section 2.1 above delivers a pulsating, unidirectional current to the load and a voltage with a positive DC average but that also contains a significant AC component. Although this circuit is satisfactory for many applications (such as a battery charger), it still contains a large AC component which in our example is equal to a value of 39.6 volts peak-peak. In the design of a DC power

supply, the aim is to produce from the AC power line a constant voltage output with a minimum of AC content. In order to do this, a means for reducing the AC component of the output voltage of the half-wave rectifier is necessary.

One way the reduction can be done is by adding a capacitor to the output of the half-wave rectifier as shown in Figure 8.6(a). The capacitor serves to fill in the gaps of the output voltage waveform during the time that the input voltage dips to zero, and in this way reduces the AC component on the output voltage (also called the *ripple voltage*). The operation of this rectifier circuit can be understood with the aid of the waveforms shown in Figure 8.6(b).

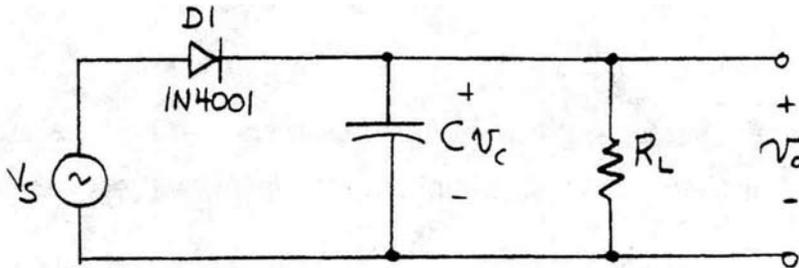


Figure 8.6(a): Peak rectifier circuit.

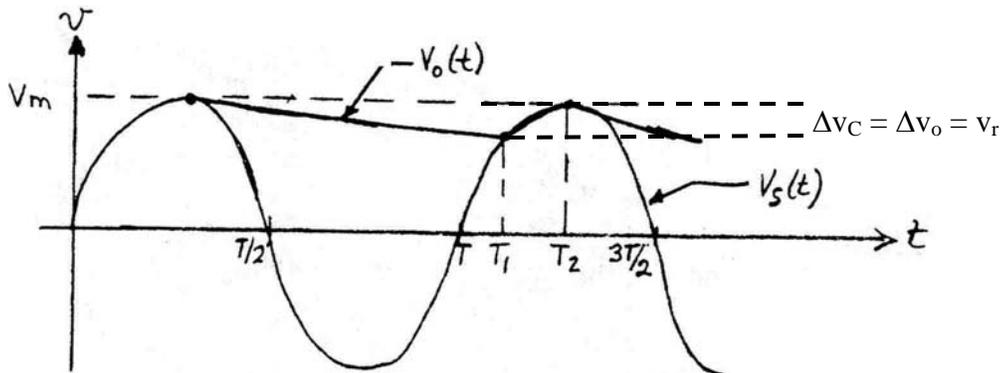


Figure 8.6(b): Waveforms in the peak rectifier circuit.

If C initially has no charge, and if v_s is applied at time $t = 0$, then as v_s increases from zero to its positive maximum of V_m , current flows in the forward direction through the diode and charge is stored in the capacitor. It follows that the voltage across the capacitor

v_c is essentially equal to v_s at every instant of time until v_s reaches its maximum value. If we assume there is no load resistor connected in parallel with the capacitor (i.e., $R_L = \infty$), then there is no way for C to discharge since the diode doesn't conduct appreciable current in the reverse direction. In this case, the charge accumulated by C during the first positive quarter cycle is trapped and cannot escape. This trapped charge maintains the voltage across the capacitor at the value of V_m , which is the maximum value of the input voltage as shown by the dotted line in Figure 8.6(b). It follows that this circuit is called a peak rectifier because its output voltage is equal to the positive peak value of the input voltage. If we assume R_L has a finite but large value, then the capacitor can discharge slowly through R_L while the diode is not conducting. Under these conditions, the output voltage across the load resistor R_L will consist of a small ripple component superimposed upon a large DC component. This is shown by the solid line labeled $v_o(t)$ in Figure 8.6(b). As R_L is made smaller, the capacitor discharges by a greater amount each cycle, and the ripple component becomes larger in magnitude. Notice that during a brief interval near the positive peak of v_s in each cycle, labeled T_1 to T_2 between T and $3T/2$ in Figure 8.6(b), a pulse of charging current flows through the diode and this pulse restores to the capacitor the charge lost through R_L during the interval when the diode is not conducting.

When the diode is not conducting, the voltage across C will discharge and is given by:

$$v_c = v_o = V_m e^{-\frac{t}{R_L C}} \quad (8.21)$$

The voltage will continue to discharge until the diode turns back on. The diode will be off during the remainder of the positive half cycle, and all of the negative half-cycle of v_s . It will turn back on at time T_1 when

$$V_m \sin \omega T_1 = V_m e^{-\frac{T_1}{R_L C}} \quad (8.22)$$

8.2.4 Full-Wave Rectifier With a Capacitor Filter

Adding a capacitor to the output of the full-wave rectifier, as shown in Figure 8.7 also serves to filter much of the AC component of the output voltage. The operation of this circuit is similar to the half-wave rectifier with a capacitor filter except the capacitor receives two charging pulses during each period of the input voltage v_s . This is shown by the waveforms in Figure 8.7(b). In this case, the capacitor charges through the diodes from v_s during time t_1 and discharges through R_L during time t_2 . Notice that this occurs twice during each period T . Being recharged twice per cycle causes the full-wave circuit to have approximately half the ripple of the half-wave circuit with the same R_L and C values.

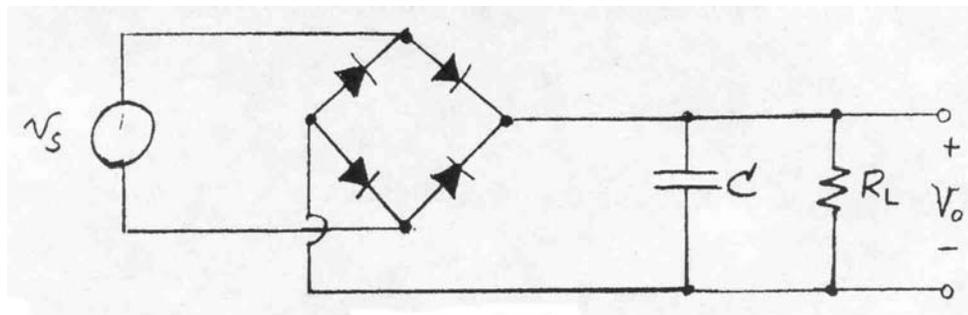


Figure 8.7(a): Full-wave rectifier circuit with capacitor filter.

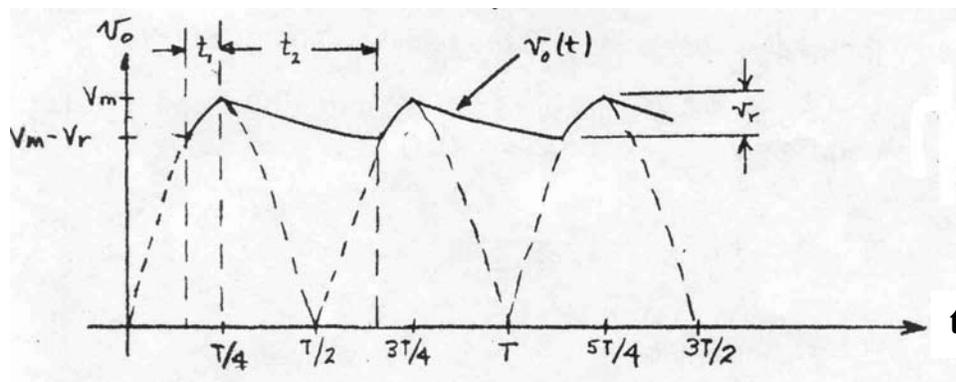


Figure 8.7(b): Waveforms in the full-wave rectifier circuit with capacitor filter.

When the ripple component of voltage is small compared to the DC component, the peak-to-peak magnitude of the ripple can be easily estimated. The peak value of v_o is V_m hence, the average value of v_o can be written as :

$$\langle v_o \rangle = V_m - v_r / 2, \quad (8.23)$$

where v_r is the peak-to-peak magnitude of the ripple component as shown in Figure 8.7(b). The ripple voltage results from the capacitor discharging through the load resistor, R_L , during the time between charging pulses (as shown by t_2 in Figure 8.7(b)).

During this interval, which can be approximated as $T/2$, i.e., half the period of v_s , since the ripple component is assumed to be small, the output voltage, v_o , is nearly constant at the value V_m . Hence the current discharging C is approximately constant and can be estimated as:

$$i_{R_L} \cong \frac{V_m}{R_L}. \quad (8.24)$$

The charge lost by C while the diodes are not conducting is :

$$\Delta q \cong \frac{T}{2} i_{R_L} \quad (8.25)$$

and the corresponding change in the capacitor voltage is :

$$\Delta v_C = \Delta v_{R_L} = v_r \cong \frac{T}{2} \frac{i_{R_L}}{C} \cong \frac{T}{2} \frac{V_m}{R_L C}, \quad (8.26)$$

where v_r represents the peak-peak value of the ripple component of v_o .

The ratio of peak-peak ripple voltage to the DC output voltage is called the **Ripple Factor (RF)**. If $v_r \ll V_m$, then RF is given by

$$RF \cong v_r / V_m \cong T / (2R_L C) . \quad (8.27)$$

Since the frequency, f , is $f = 1/T = \omega / 2\pi$, then it follows that:

$$RF \cong \pi / (\omega R_L C). \quad (8.28)$$

The % Ripple is obtained from the Ripple Factor and is given by

$$\% \text{ Ripple} = RF \times 100\% = (v_r / V_m) \times 100\% . \quad (8.29)$$

The resultant output voltage waveform for a full-wave rectifier circuit with a $1000\mu\text{F}$ capacitor and a 100Ω load resistor is illustrated in Figure 8.8. First note that the scales are both normalized. So, when the output load voltage is 1, it is equal to the maximum value of v_o , which is V_m , and when the time scale is 1, this is equivalent to one period, T , of the input voltage.

One of the waveforms provides an illustration of the load voltage without any capacitor and is indicated by using the "□" symbol. The other waveform provides an illustration of the load voltage with a $1000\mu\text{F}$ capacitor and is indicated by using the "+" symbol. Notice that without the capacitor, the normalized peak-peak ripple voltage component is 1.0 whereas with the capacitor it is reduced to less than 0.1.

As another example, assume the capacitor in Figure 8.7(a) is $1000\mu\text{F}$ and R_L is $3.9\text{k}\Omega$. If we also assume that the transformer secondary output is a 28V rms sinusoidal signal, then $v_s = 28\sqrt{2} \sin \omega t$ and the peak or maximum value of the input voltage is $28\sqrt{2} \cong 39.6 \text{ V}$. It follows that the voltage across the $3.9\text{k}\Omega$ load resistor will have a maximum value of 39.6 V and the resultant average load current, I_L , through R_L can be estimated as:

$$I_L \cong (39.6\text{V.})/(3.9\text{k}\Omega) = 10 \text{ mA} . \quad (8.30)$$

It also follows that for the $1000\mu\text{F}$ capacitor supplying a load current of approximately 10 mA to the external circuit with a full-wave rectified source at 60 Hz ($\Delta t = 1/120$ second), the ripple will be reduced to 83.3 mV as indicated by using Eq. (8.26). This is significantly less than the 39.6 V ripple obtained without the $1000\mu\text{F}$ capacitor. In this case the Ripple Factor is:

$$\text{RF} = v_r / V_{\text{DC}} \cong (83.3\text{mV.})/(39.6\text{V.}) = 0.00208 \approx 0.21\% \quad (8.31)$$

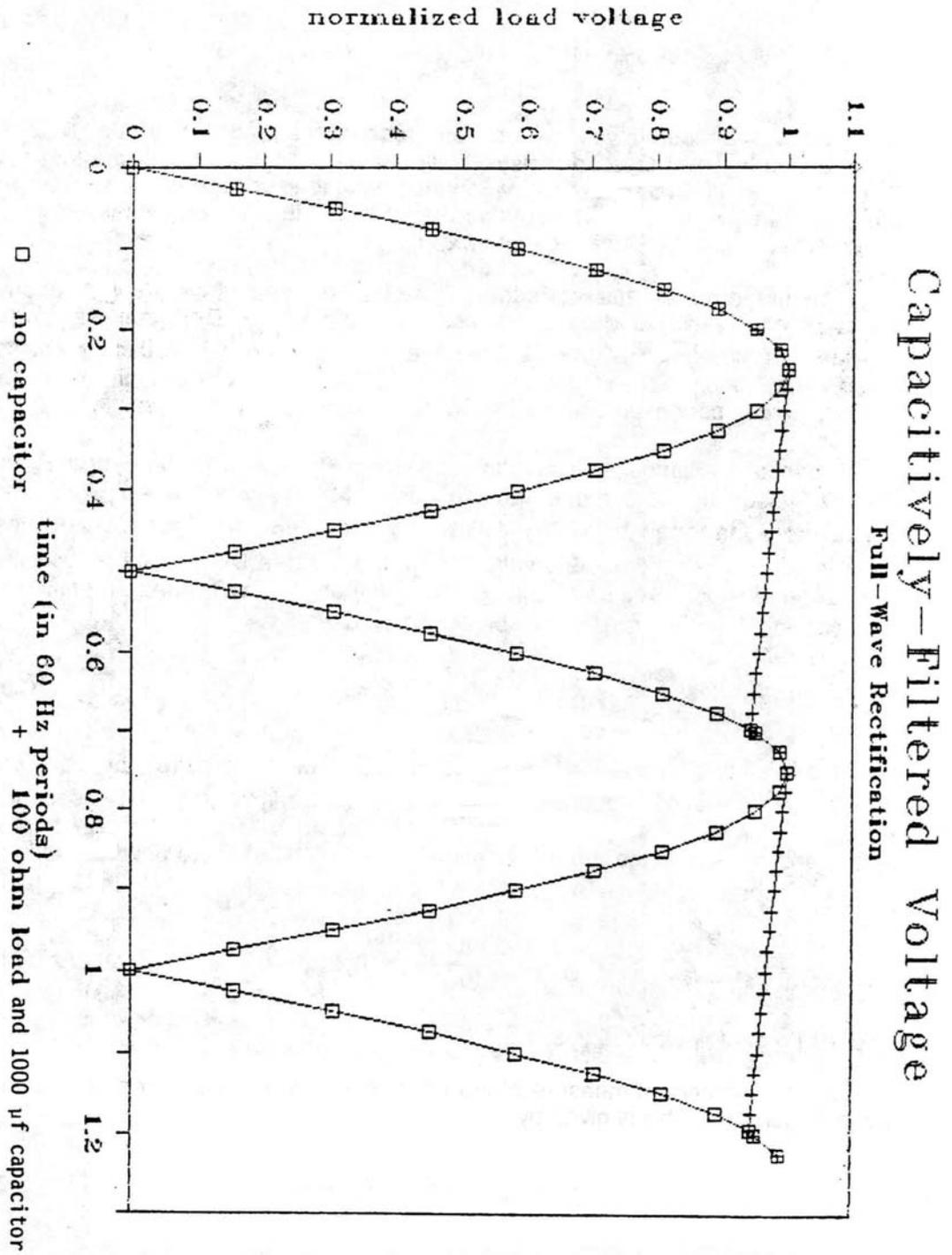


Figure 8.8: Waveforms for the full-wave rectifier circuit.

Another important measure of the performance of a DC power supply is the **Voltage Regulation**. This is given by:

$$\text{Voltage Regulation (VR)} = \frac{V_{NL} - V_{FL}}{V_{NL}} 100\% \quad (8.32)$$

where V_{NL} is the output voltage at no load (i.e., $R_L = \infty$ and $I_L = 0$) and V_{FL} is the output voltage at full load (i.e., $I_L = I_{L(\max)}$). This is an important specification because it defines the output voltage over the operating range of the power supply. Thus, given a 50 volt DC power supply capable of providing a current of 500 mA with a Load Regulation of 0.025, it follows that when the supply is providing the maximum current of 500 mA, its output voltage from Equation (8.30) above is given by

$$V_{FL} = V_{NL} - V_{NL} * (\text{VR}) = 50 - 50 (0.025) = 48.75 \text{ V.} \quad (8.33)$$

Exercise 1. Half-Wave Rectifier and Filter Capacitor

(a) Construct the circuit shown in Figure 8.9 below

(b) Use both channels of the oscilloscope to observe the output voltage of the transformer secondary voltage and the voltage across the 3.9 k Ω resistor. Make a copy of each waveform noting its shape, periodicity and peak voltage. Take appropriate measurements with the DMM's and the oscilloscope to determine the average or DC component, the AC component, and the RMS values of each waveform. Compare your measurements to the calculated values based upon their peak values.

(c) Using the oscilloscope, make a hardcopy of the waveform across the diode and measure the diode's forward bias voltage, $V_{D(\text{ON})}$, and the peak inverse voltage, $V_{D(\text{piv})}$. This can best be done by measuring the voltage across the diode directly using the scope.

(d) Now add a 1 to 10 μF capacitor decade box across R_L as shown in dashed lines in Figure 8.9. Initially set the value of the capacitor to 1 μF and copy the output voltage

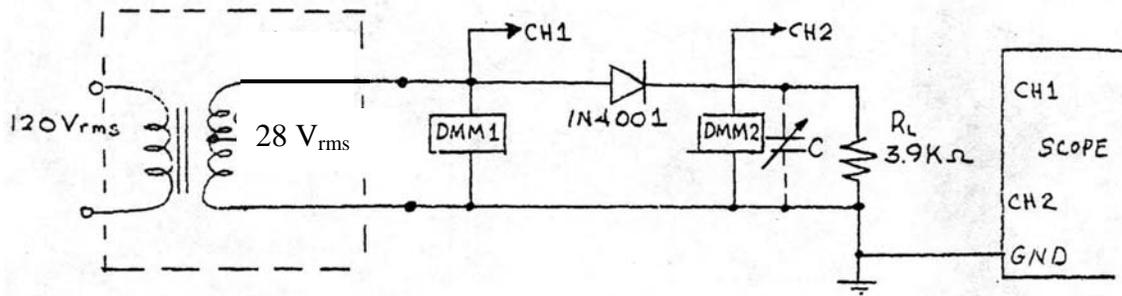


Figure 8.9: Circuit for Exercise 1.

across R_L compared to the output voltage of the secondary - again noting the waveform shape, period and peak-to-peak voltage for each signal. Use the DMM and oscilloscope and measure the DC component and the RMS value of the AC component of the output voltage across the $3.9\text{k}\Omega$ resistor. Increase the value of the capacitor from $1\mu\text{F}$ up to $10\mu\text{F}$ and observe the change in the output voltage. Make a hardcopy and take measurements at values of $5\mu\text{F}$ and $10\mu\text{F}$, respectively. What happens to the DC and AC components as the capacitor value is increased?

Exercise 2. Full-Wave Rectifier

Construct the circuit shown in Fig. 8.10 below using the four diode DB102 bridge as shown. Repeat steps 1(b) and 1(c) above. In this case, notice that you can only use the

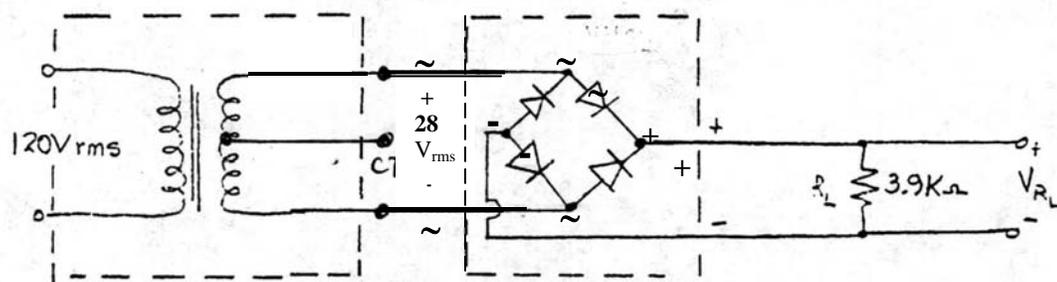


Figure 8.10: Circuit for Exercise 2

scope to make one measurement at a time because the secondary output of the trans-

former is isolated and the ground connection of the scope is not isolated from chassis ground. First, measure the output voltage of the transformer secondary and then measure the voltage across the $3.9\text{ k}\Omega$ resistor. Also, you can measure the voltage across one of the diodes within the DB102 bridge by placing the scope probe on the plus (+) side of the $3.9\text{ k}\Omega$ resistor and the scope ground on either output of the transformer secondary.

Exercise 3. Full-Wave Rectifier With a Filter Capacitor.

Construct the circuit illustrated in Figure 8.11 with the inductor replaced by a short circuit. Measure the DC voltage and the peak-to-peak ripple component of the voltage across R_L for DC load currents between 0 and 100 mA using 10 mA increments. Notice that the load current can be varied by changing the resistance value of the decade resistor box until the DMM used as a DC ammeter reads the appropriate value. Also, the DC voltage can be measured with the second DMM and the peak-to-peak ripple voltage can be measured with the scope AC coupled.

WARNING - (1) This circuit provides **NO SHORT CIRCUIT PROTECTION, SO DO NOT** adjust the decade box to all 0's (start off with it set to all 9's) and (2) Note that the **capacitor used in this circuit is electrolytic** and; as a result, is polarized and thus must be connected accordingly.

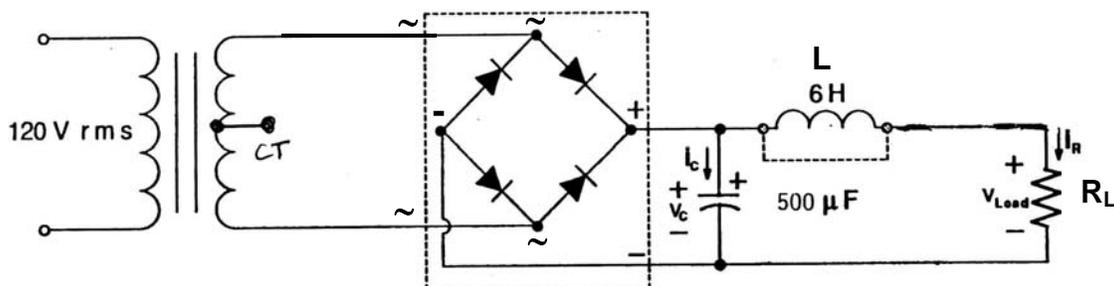


Figure 8.11: Circuit for Exercise 3.

8.2.5 Full-Wave Rectifier With a LC Filter.

When the previous Exercise is carried out, it becomes apparent that the voltage ripple increases as the load current increases. Recall that when using a 1000 μ F capacitor in our previous example, it was found that the approximate voltage ripple was 83.3 mV for a load current of 10 mA. You should be able to show that for a load current of 100 mA, the approximate voltage ripple is 833 mV and for 1 A of load current the ripple is 8.83 V

The undesirable increase of the voltage ripple with increasing load current may be offset through the use of a component that stores additional energy as the load current increases. An inductor placed in series with the load resistor will perform this function. The inductor-load combination acts as a R - L low-pass filter to reduce the voltage ripple across the load as its resistance decreases. The voltages at the capacitor, v_C , and at the load, v_L , may be approximated using the first two terms of a Fourier Series as

$$v_C \cong V_{DC} + \frac{1}{2}(\Delta v_C) \sin \omega t \quad (8.34)$$

$$v_L \cong V_{DC} + \frac{1}{2}(\Delta v_L) \sin(\omega t + \phi) \quad (8.35)$$

where $f = 120$ Hz and $\omega = 240\pi$. However, an inspection of Figure 8.11 shows that the ratio of the two ripple voltages, Δv_C across the capacitor, and Δv_L across the load is:

$$\frac{\Delta v_L}{\Delta v_C} = \frac{1}{\sqrt{1 + \left(\frac{\omega L}{R_L}\right)^2}} \quad (8.36)$$

Now, since the time interval, Δt , between capacitor recharging pulses is $T/2$, then

$$\Delta t = \frac{T}{2} \cong \frac{2\pi}{\omega} \quad (8.37)$$

it follows that :

$$\Delta v_L \cong \frac{\frac{2\pi V_M}{\omega R_L C}}{\sqrt{1 + \left(\frac{\omega L}{R_L}\right)^2}}. \quad (8.38)$$

In the limit of small load resistance, i.e., $\omega L/R_L \gg 1$, the ripple saturates to a value:

$$v_r = \Delta v_L \cong \frac{2\pi V_M}{\omega^2 LC} \quad (8.39)$$

With $\omega = 2\pi$ (120 Hz) (equivalent to full-wave rectification at 60 Hz) and a 400Ω load resistor, an inductor $L > 0.5\text{H}$ is required to reach this limit. As with the approximate calculations for capacitive filtering this calculation gives an upper limit on the voltage ripple. The results of a somewhat more exacting, albeit tedious, calculations are shown in Figure 8.12

Exercise 4. Full-Wave Rectifier with a L-C Filter.

With the 6 Henry inductor installed in the circuit of Figure 8.11, repeat the measurements of Exercise 3 above.

8.3 Transistor Regulation

The circuit of Figure 8.11 is a substantial improvement over the previous circuits, but still leaves much to be desired. The voltage ripple is still excessive for many applications, the output regulation is poor, power is lost in the inductor winding resistance, and there is no short circuit protection. Additionally, the output voltage is primarily set by the transformer and is not easily varied. These disadvantages are largely overcome in the transistor regulator circuit of Figure 8.13.

In this circuit, the output voltage is set by the Zener diode and the transistor base-emitter forward-bias voltage. With the components shown, the source voltage is 6.2V (the Zener diode voltage) and the transistor base-emitter junction voltage is $\cong 0.7\text{V}$. This gives a load voltage of approximately 5.5V. The $2.7\text{k}\Omega$ resistor in series with the Zener diode maintains a minimum current of 10mA through the diode for all load currents of

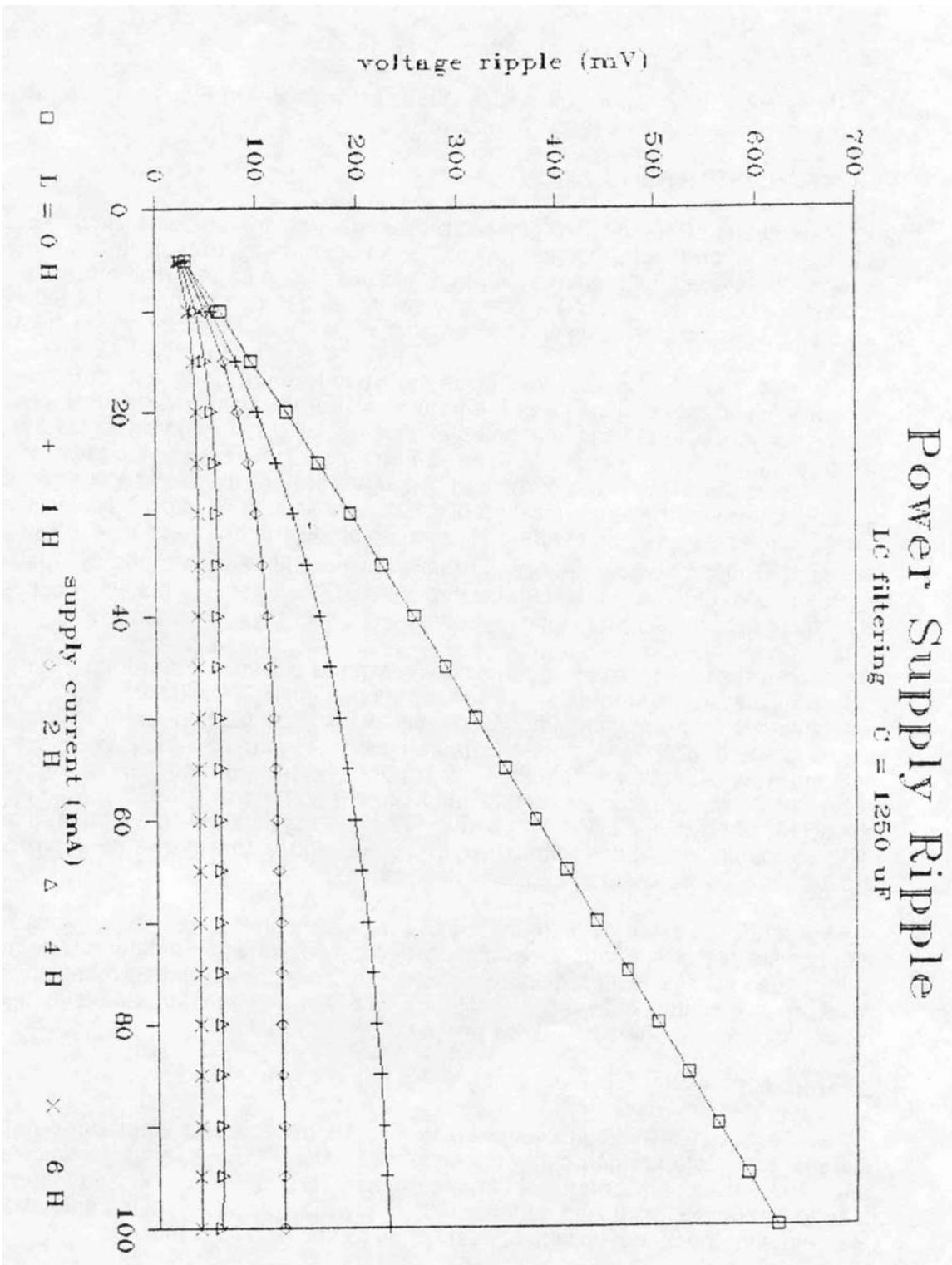


Figure 8.12: Effect of inductor size on power supply ripple.

interest (note the location of the current-limiting resistor), keeping the Zener diode operating in a region where it has a small differential resistance, defined as $R_{\text{dif}} = \Delta v_z / \Delta i_z$. Thus, moderate changes in the resistor-diode series voltage will result in proportional changes in the current through these components, but will produce only minute changes in the Zener diode voltage.

The transistor serves to deliver relatively large currents to the load with a relatively small current in the resistor-Zener diode circuit. The 2N3055 transistor used here has a DC current gain of approximately 40 so that a load current of 100mA draws a mere 2.5mA from the base-biasing circuit. The reverse-biased collector-base junction is capable of withstanding any voltage less than the reverse-voltage breakdown value for this transistor, which is 60V. Consequently, this circuit will regulate the output voltage at approximately 5.5V as long as the collector-base voltage isn't less than 0.5V (the onset of saturation) or greater than 60V (the onset of voltage breakdown in the transistor).

Note that one of performance criteria for transistor regulators is the Ripple Rejection (RR). RR is the ripple voltage across the load divided by the ripple voltage across the capacitor in decibels., i.e.,

$$RR = 20 \log_{10} (v_{RL}/v_C) \quad (8.40)$$

Exercise 5. Transistor Regulator.

(a) Construct the circuit of Figure 8.13. Use the DMM's to record $V_{Z(\text{DC})}$ and $V_{\text{Load}(\text{DC})}$ as the load resistor is varied from 1Meg Ω to 50 Ω in a 1, 0.5, 0.2 ...sequence.

(b) With a load resistor of 50 Ω , record the DC and AC voltages across the 500 μF capacitor and the DC and AC voltages across the 50 Ω load resistor using the DMMs.

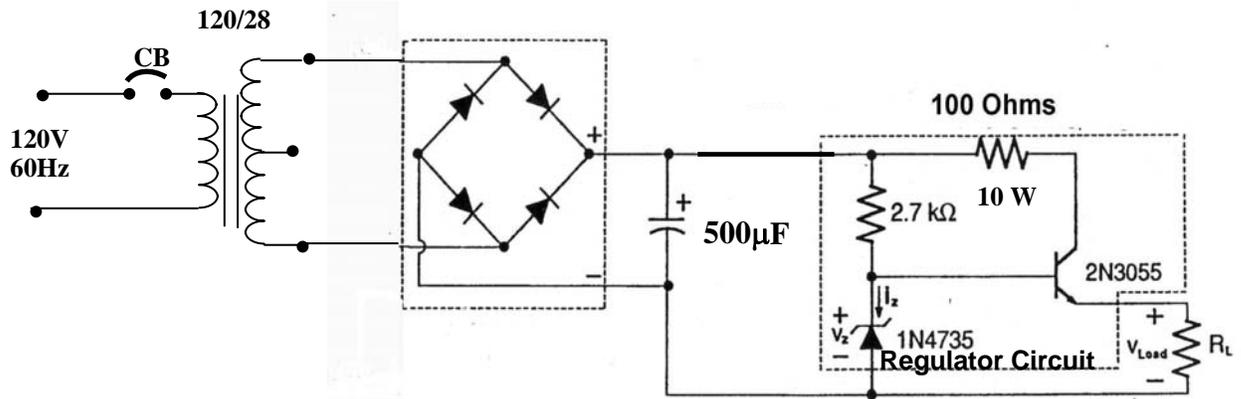


Figure 8.13: Transistor regulator circuit.

8.4 Active Regulation

The circuit of Figure 8.13 performs quite well for all but the most demanding applications, and yet has a few drawbacks. The output is not continuously variable, being set by the choice of Zener diode, and there is no compensation for drift in the output voltage. This latter is particularly important due to the lack of temperature compensation for changes in the base-emitter forward bias voltage and variation in DC current gain as the transistor dissipates power and gets warmer. While there are many simple schemes for incorporating temperature compensation and adjustments for deviations in the output voltage, we will not pursue these, but instead we will turn our attention to commercial integrated circuit regulators such as the LM317, which is used in the circuit of Figure 8.14. Conceptually, the LM317 is quite similar to the regulator circuit employed previously but with numerous refinements. Under *proper operating conditions* it exhibits good regulation as the load or input voltage is varied, with a small current through the adjust terminal so that the input current is nearly identical to the load current. The LM317 also employs a significant amount of compensation circuitry to insure a

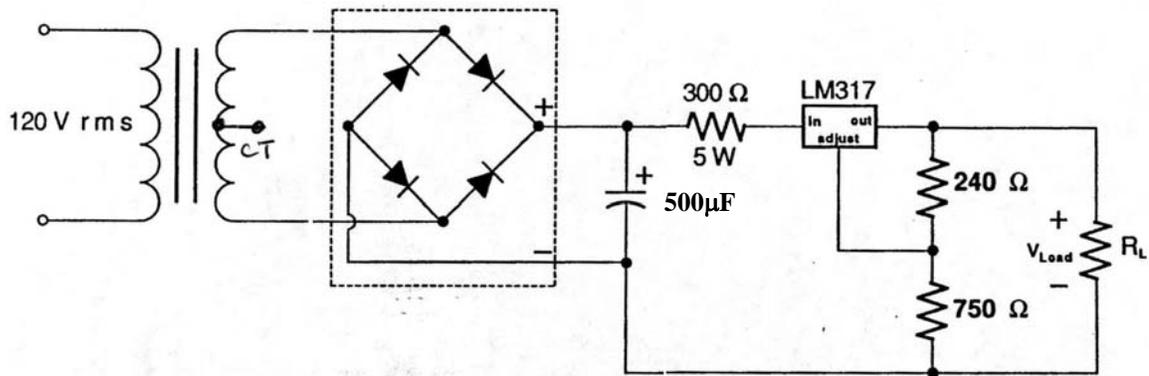


Figure 8.14: Active regulator circuit

stable output voltage (i.e., non-oscillatory) over a wide range of operating conditions. An idealized equivalent circuit for this device is shown in Figure 8.15. The similarities

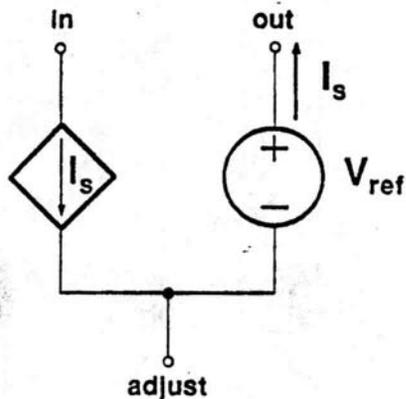


Figure 8.15: Simplified circuit model for the LM317 regulator.

between this model and that for an ideal active transistor should be apparent. V_{ref} is the output voltage, which is set internally to 1.2V for the LM317. Other commercial regulators have output voltages that are more commonly required. An example is the LM7805, which has an output voltage, non-variable, of 5V. For the LM317, proper operation requires that the input to output voltage difference remain between 3V and 40V and that the output terminal current be at least 10mA. Under these conditions the

manufacturer specifies a maximum output load voltage regulation of 0.5% (or 25mV if $V_{in} - V_{out} < 5V$), a maximum regulation due to change in input voltage of 0.07% per Volt of change in the input, and a typical ripple rejection of 65dB with full wave rectification at 60 Hz.

An output voltage of 1.2V from the LM317 may, at first glance, seem to have limited utility, but with the proper circuit connections it may be used to produce a regulated output voltage of almost any value. Consider the circuit of Figure 8.14. A current of 5mA ($1.2V / 240\Omega$) passes through the 240Ω resistor. Since the current in the adjust terminal is quite small, (typically $50\mu A$.) and stays substantially constant as the load current varies, any reasonable resistor value connected between the adjust terminal and the power supply common will also conduct 5mA. In this way the LM317 may be used as a constant current source, where the constant current emanates from the adjust terminal and the 240Ω resistor. To construct an approximate 5V source we need merely to connect a 750Ω resistor in this location. The voltage across this resistor is then 3.75V, which causes the net output voltage to common to be 4.95V. Any additional current required by a load resistor is supplied by the regulator output without affecting the output voltage that remains at 4.95V.

Exercise 6. Active Voltage Regulator

Construct the circuit illustrated in Figure 8.14 and measure the output voltage and ripple for load currents between 0 and 100mA.

8.5 Report

8.5.1 Show a copy of the load resistor voltage observed for the half-wave rectified

unfiltered circuit. What was the DC component and RMS voltage from your measurements and how does this compare to the calculated values? Now, show a copy of the voltage waveform observed across the diode and indicate the value of the forward biased and peak inverse voltages that you observed.

8.5.2 Show the load resistor voltages observed for the half-wave rectified circuit with the $1\mu\text{F}$ capacitor compared to the $10\mu\text{F}$ capacitor. Using your measured values, specify the DC output voltage and determine the % ripple for values of $1\mu\text{F}$, $5\mu\text{F}$, and $10\mu\text{F}$.

8.5.3 Show the load resistor voltage observed for the full-wave rectified unfiltered circuit. What were the DC component and RMS values from your measurements and how do they compare to the calculated values? Next present the copy of the voltage waveform observed across one of the diodes and indicate the value of the forward bias and peak inverse voltages that you measured.

8.5.4 Use your data to construct a table and plot the values of the DC and ripple components of the load voltage as a function of load current for the full-wave rectified circuit with just the capacitor as filter. How does the ripple component measured in V_L compare to estimates obtained from calculated results assuming only a capacitor is used as a filter? What is the load voltage regulation for this DC supply? What is the % ripple at full load?

8.5.5 Repeat the table and plot for the circuit using the LC filter. What is the voltage regulation and % ripple at full load for this supply? Why is the average DC output of this supply less than the one when only the capacitor was used? How does the load regulation and % ripple of this supply compare with the one that only used a capacitor? Finally, if you wanted to use this supply but needed the same DC output as the supply with only a capacitor as a filter, what change could you make?

8.5.6 For Exercise 5, make plots on the same graph of $V_{Z(DC)}$ and $V_{RL(DC)}$ versus R_L using a log scale from 50Ω to $1 M\Omega$. Calculate load Voltage Regulation (VR) in percent. What causes it to differ from 0%? What was the ripple voltage at $R_L = 50 \Omega$? Compute the Ripple Rejection (RR) in dB for $R_L = 50 \Omega$. For a load of 50Ω , calculate the power dissipated by the transistor and by the 100Ω current limiting resistor.

8.5.7 Describe the performance of the LM317 regulator used in this experiment. How did the output voltage vary as the load current approached zero? What voltage ripple was observed and what was the voltage regulation of the circuit? Does the LM317 meet the performance specifications given by the manufacturer that are applicable here?

8.5.8 Design Problem - Design a DC power supply, similar to the one shown in Figure 8.11, that includes a full wave bridge rectifier (DB 102) and filtering provided by an inductor and a capacitor. The power supply should satisfy the following specifications.

Power source: 120 V, 60 Hz, Single Phase AC

Output current: 1000 mA max

Output voltage: $11 V_{DC}$ at half load (500mA) and $10V_{DC}$ at full load (1000 mA)

Ripple voltage: Less than $0.3 V_{p-p}$ for all currents.

The design documentation should include the following:

1. A schematic diagram of the power supply circuit,
2. The voltage ratio for the transformer,
3. The selected capacitor and inductor values and inductor coil resistance,
4. Verify that ripple voltage specifications are met,
5. Calculate the output voltage at 100 mA.