EE315 - Electronics Laboratory

Experiment - 2 Simulation
Rectifier Circuits

Background

Rectifier circuits are the major components of DC power supplies. This experiment focuses on the AC to DC voltage rectification methods and a couple of basic filtering techniques. Ideally a power supply is expected to provide a pure DC output regardless of changing input and load conditions. Following are the essential specifications that determine quality of power supplies.

Nominal Output Voltage and Rated Current are the basic parameters that describe the intended usage of a power supply. Rated current specifies the DC current a power supply can provide continuously under normal operating conditions. Nominal output voltage is the DC voltage specified for a load that draws the rated current.

Load Regulation of a power supply indicates how much the DC output voltage varies as its load changes. Traditionally, load regulation is defined as a percentage:

$$\%\ \textit{Load Regulation} = \frac{V_{OutFullLoad} - V_{OutMinLoad}}{V_{OutNominal}} \times 100\ \% \qquad [1]$$

Where:

$V_{OutFullLoad}$ is the output voltage for a load that draws the greatest current (with the lowest specified load resistance).

$V_{OutMinLoad}$ is the output voltage for a load that draws the least current (with the highest specified load resistance - possibly open circuit for some types of linear supplies, usually limited by pass transistor minimum bias levels).

$V_{OutNominal}$ is the output voltage for the typical specified operating load.

For integrated DC voltage regulators and switching power supplies, load regulation is defined without normalizing to nominal output voltage and then has the units of volts.

Line Regulation of a power supply is the capability to maintain a constant output voltage against changes to the input voltage. Line regulation is measured or specified for a constant load current while the input voltage changes within a range that allows proper operation of the power supply. Similar to the load regulation, line regulation can be expressed as percent of change in the output voltage or directly without normalizing to nominal voltage.

Output Ripple is the measure of AC content in the DC power supply output as a result of periodic variations in the output voltage. Output variations due to changing load conditions are considered under load regulation and these variations do not contribute to output ripple. A common specification of output ripple is the **ripple factor** given by the ratio of RMS value of AC voltage to the DC voltage at the output:

$$\textit{Ripple Factor} = \frac{V_{AC\text{-}RMS}}{V_{DC}} \qquad [2]$$

Ripple factor is a measure of how "dirty" is the DC output of a power supply. A common source of output ripple is the voltage variations in the output of rectifier circuitry at twice the line frequency or its upper harmonics. This produces the so called "hum" in audio amplifiers, blurring of the display on an oscilloscope, or otherwise causing extraneous signals in instrumentation. In case of switching power supplies, the main source of ripple is the high frequency switching circuitry of the supply.

Power efficiency is the ratio of DC power delivered at the output to the power required at the input. A low-efficiency power supply wastes more power compared to a high-efficiency supply and it may present a difficult cooling problem. For example, a power supply working at 75 % efficiency requires 20 W of power at the input in order to deliver 15 W. The 5 W difference is the power dissipated in the power supply and it must be transferred to the surrounding air through a cooling mechanism.

Half-Wave Rectifier

A half-wave rectifier circuit is shown in Figure 1. v_{line} is the AC source that feeds transformer primary winding, v_S is the transformer secondary output, and v_L is the rectified voltage on the load resistor, R_L. In power supply applications, it is common to use a transformer to isolate the DC supply outputs from the high voltage AC line. The diode conducts during the positive half-cycle of the transformer output and v_L follows the transformer voltage. The voltage across R_L is slightly less than the voltage supplied by the transformer due to the forward bias voltage and internal resistance of the diode.

During the negative half-cycle the diode is off and no voltage is present at the output. Assuming the diode is ideal (i.e. zero forward bias voltage), the average value of this rectified waveform is

$$V_{LDC} = \frac{1}{T}\int_{t=0}^{T/2} V_{SP}\, \sin(\omega t)\, dt = \frac{V_{SP}}{\pi} \qquad [3]$$

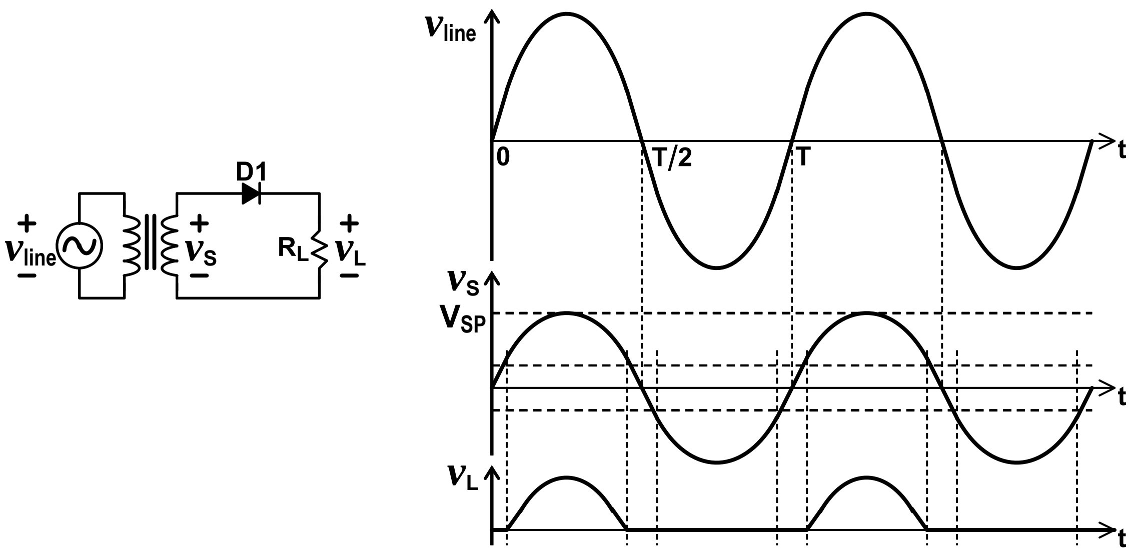


Figure 1. Half-wave rectifier circuit and resulting voltage waveforms.

Full-Wave Rectifier with Center-Tapped Transformer

A more efficient use of the AC voltage is achieved by rectifying both half cycles of the transformer voltage. This can be done using two diodes with a ***center-tapped transformer*** where the center tap is connected to ground as shown in Figure 2. One of the diodes conducts in the positive half-cycle and the other diode conducts in the negative half-cycle. Frequency of the resulting rectified voltage waveform is twice the line frequency.

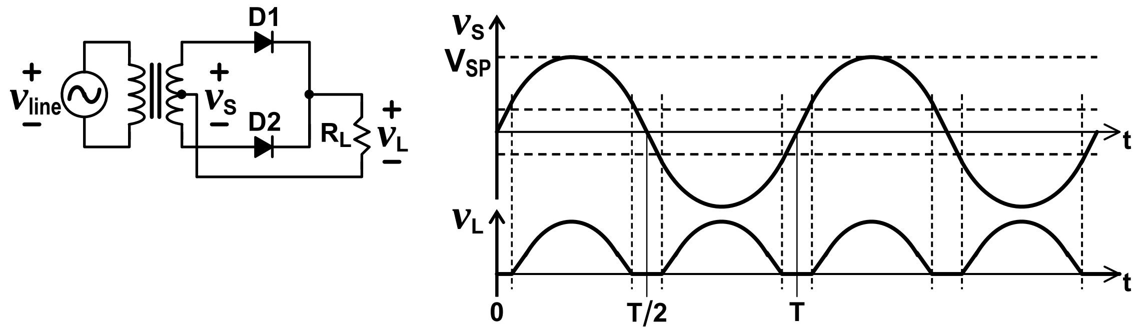


Figure 2. Full-wave rectifier with a center-tapped transformer.

The average value of this full-wave rectifier output is given by (assuming ideal diode behavior again):

$$V_{LDC} = \frac{2}{T}\int_{t=0}^{T/2} \frac{V_{SP}}{2}\, sin(\omega t)\, dt = \frac{V_{SP}}{\pi} \qquad [4]$$

V_{LDC} calculated for the half-wave rectifier and the V_{LDC} obtained here are the same for a given transformer peak output voltage, V_{SP}. Transformer in the half-wave rectifier supplies current in the positive half cycle only. The center-tapped transformer supplies current in both positive and negative half cycles, but only half of the transformer secondary winding is active at a time.

Full-Wave Bridge Rectifier

It is possible to obtain full-wave rectification without a center-tapped transformer by using the **bridge rectifier** shown in Figure 3. The four diodes can be discrete components or integrated into a single *bridge rectifier* package. During the positive half-cycle of the transformer output, two of the diodes, D1 and D3, are forward biased and D2 and D4 are reverse biased. Therefore, D1 and D3 are conducting in series with R_L in the positive half-cycle. The resulting voltage across R_L is equal to that of the transformer output minus the voltage drop across the two diodes. In a similar way, the diodes D2 and D4 are forward biased in the negative half cycle and D1 and D3 are reverse biased.

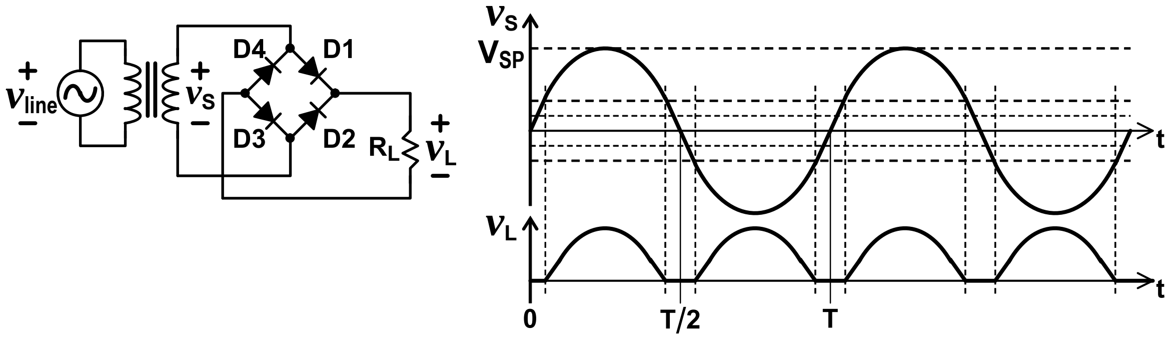


Figure 3. Bridge rectifier circuit.

Bridge rectifier produces approximately twice the DC output voltage compared to the full wave rectifier with center-tapped transformer, for the same transformer voltage:

$$V_{LDC} = \frac{2}{T}\int_{t=0}^{T/2} V_{SP}\, sin(\omega t)\, dt = \frac{2\, V_{SP}}{\pi} \qquad [5]$$

This expression does not take into account the voltage drop across the diodes too. A disadvantage of bridge rectifier is that the DC voltage drop across the two diodes in series is greater than the voltage drop across one diode in the full wave rectifier with center-tapped transformer.

Capacitive Filtering

All methods of rectification produce some ripple in addition to the DC output. Most applications on the other hand, require as smooth as possible DC power with minimal ripple. Full-wave rectification is preferred over half-wave rectification, because the continuity of the DC output makes the filtering easier. A common method of reducing ripple is to add a large filter capacitor in parallel with the load.

The load voltage, v_L, with a filter capacitor at the full-wave rectifier output is shown in Figure 4.a. There are two components of the periodic waveform of v_L. The positive slope region follows the transformer voltage as the rectifier charges the capacitor. The negative slope region is an exponential decay as the capacitor discharges through R_L. Note that the average voltage across R_L is greater than what it would be without the capacitor. Rectifier provides current when it charges the capacitor only. This means that the peak value of rectifier current must be higher than the average current in a period, because the average rectifier current output must be equal to the average load current. Therefore the peak current demand from the transformer secondary winding and the rectifier diodes are high, and the diodes must withstand these large peak currents without being damaged.

It is difficult to write an exact expression for the filtered rectifier voltage. The output voltage can be approximated by a triangular waveform, where charge and discharge cycles are represented by straight lines as shown in Figure 4.b. The peak value of this wave is V_{LP}, given by the peak transformer voltage less the forward-bias voltage drop on rectifier diodes. If the peak to peak ripple voltage is V_{rplPP}, then the average value of the output, V_{LDC}, is approximately given by:

$$V_{LDC} = V_{LP} - \frac{V_{rplPP}}{2} \qquad [6]$$

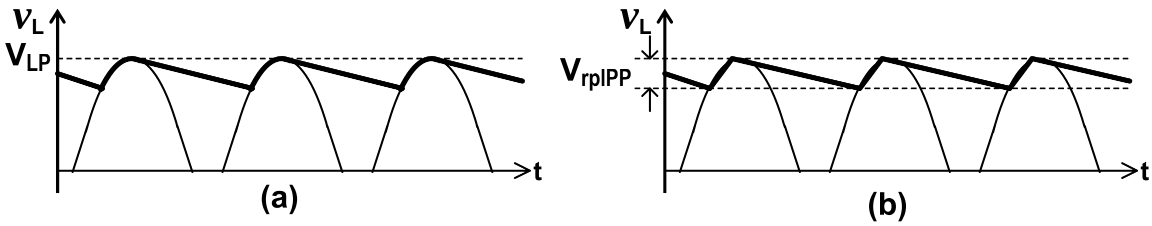


Figure 4. a) Capacitor-filtered rectifier output waveform,
b) Triangular approximation to the ripple waveform

The RMS value of this triangular wave is independent of the slopes or lengths of the straight lines and depends on the peak value only. Calculation for the RMS ripple voltage for the triangular approximation yields:

$$V_{rplRMS} = \frac{V_{rplPP}}{2\sqrt{3}} \qquad [7]$$

Then the ripple factor is given by

$$\textit{Ripple Factor} = \frac{V_{rplRMS}}{V_{LDC}} = \frac{V_{rplPP}}{2\sqrt{3}\,V_{LDC}} \qquad [8]$$

The ripple amplitude increases with the increasing load current and decreases with a larger capacitance. In order to keep the ripple low and ensure good regulation large capacitors (hundreds of μF) must be used. Electrolytic capacitors are the most common type of capacitors for this rectifier application. Electrolytic capacitors are polarized, and care must be taken **to match the + or - capacitor polarity with the voltage polarity in a circuitry** to avoid an explosion.

A second filter capacitor and a resistor are sometimes used to decrease the ripple as shown in Figure 5. This configuration is called as **π-type filter.**

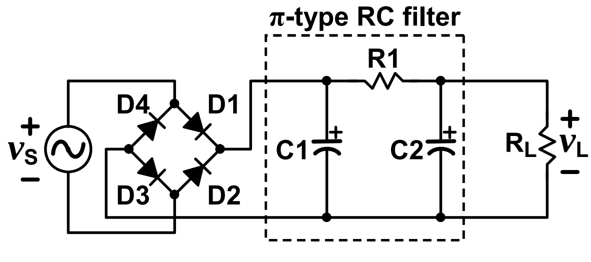


Figure 6. π-type RC filter to reduce ripple voltage..

The no-load voltage of a capacitive filter is equal to the peak transformer voltage less the voltage drop on the rectifier diodes. The disadvantages of capacitive filtering are the relatively poor regulation, the high ripple at large loads and the high peak currents that the diodes must withstand. Poor regulation means that the DC voltage at the load terminals depends on the load current. This dependence may be considered in terms of the output resistance or Thevenin resistance of the power supply that does not have the ideal value of zero. A quantity of interest is the incremental output resistance defined as $\Delta v_L/\Delta i_L$, since the load voltage in general does not change in a linear fashion with current.

Zener Diode Regulation

A simple method of voltage regulation is to connect a zener diode in parallel with the load as shown in Figure 7.a. Figure 7.b is the typical current-voltage characteristic of diode. A zener diode behaves like a regular diode when it is forward biased. When the diode is reverse-biased, a small current, $\mathbf{I_S}$, called the reverse saturation current, flows. The reverse current remains relatively constant despite an increase in the reverse bias until the zener breakdown voltage is reached. Here the reverse current starts rising rapidly as a result of the avalanche effect, and zener breakdown (a sharp increase in current) occurs. The diode continues to function normally, as long as the current through the diode is limited by the external circuit to a level within its power handling capabilities. The breakdown voltage, $\mathbf{V_Z}$, of a zener diode depends on diode construction and material. Zener diodes are used as voltage regulators and as voltage references.

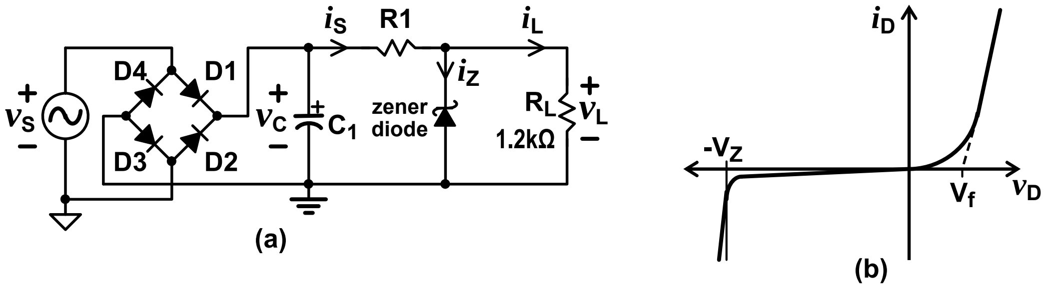


Figure 7. a) Zener shunt regulator, b) Zener diode current versus voltage characteristics.

Once the reverse breakdown voltage is reached, i_Z increases very rapidly in response to any further attempt to increase v_L. If the voltage on the filter capacitor, v_C, increases, then the voltage drop on $\mathbf{R_S}$ increases by the same amount, while v_L remains relatively constant. In a way, the zener diode takes away any excessive power that should not be delivered to the load. For a wide range of $\mathbf{R_L}$ values, the zener diode must be capable of conducting an average current given by

$$I_{Zavg} = \frac{v_C - V_Z}{R_S} \qquad \text{(for } v_C > V_Z \text{ always).} \qquad [9]$$

Then the average power dissipated on the zener diode is equal to:

$$P_{Zavg} = V_Z\, I_{Zavg} = V_Z \frac{v_C - V_Z}{R_S} \qquad \text{(for } v_C > V_Z \text{ always)} \qquad [10]$$

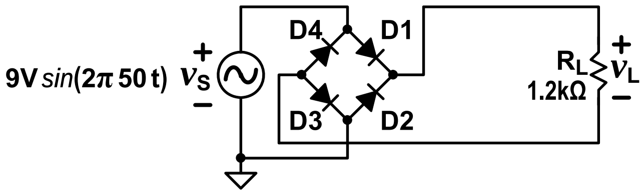
For example, if v_C = 10 V, $\mathbf{R_S}$ = 50 Ω, and $\mathbf{V_Z}$ = 5 V, then

$$P_{Zavg} = V_Z \frac{v_C - V_Z}{R_S} = 5\ \frac{10 - 5}{50} = 0.5\ \text{W}$$

The regulator output resistance seen by the load is the dynamic resistance of the avalanche diode in parallel with $\mathbf{R_S}$. Usually the dynamic resistance of the diode is very small (~1 Ω), so the zener regulation circuit is fairly good except for its lack of adjustability and limited range of load current. To provide for adjustability and improved regulation over a wide range of conditions, the difference between the zener-regulated voltage and the load voltage can be sensed, amplified, and used to control the load current with a transistor. For many voltage ranges, this type of regulator is available as an IC requiring only a few, if any, external components.

Procedure

1. Build the following circuit. Use the function generator to obtain the specified AC input voltage.



Verify the amplitude and frequency of the output waveform on the load resistor, $\mathbf{R_L}$.

Peak voltage: ___________

Waveform period: ___________ Frequency ___________

Note that, **you cannot connect the ground attachments of scope probes to $\mathbf{R_L}$ terminals**, because that will short circuit either **D2** or **D3** through the ground wires of AC power cables. The ground connectors of scope probes should be attached to the ground wire at the signal generator output. You should setup the scope for differential voltage measurements by using two probes.

1.a) Which diode(s) is/are on during the positive and negative cycles of v_S?

1.b) v_S frequency is 50 Hz. Why the v_L frequency is 100 Hz?

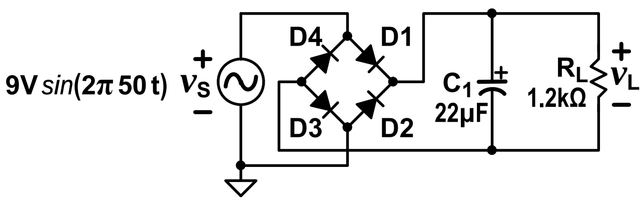
1.c) Calculate the average power dissipated on all four rectifier diodes (assume that each diode is ON for exactly one half cycle of v_S for simplicity).

1.d) How much power would have been dissipated on the diodes in total, if the same output waveform was obtained using a full-wave rectifier with a center-tapped transformer?

2. Measure and record the peak and average values of the voltage output for the following $\mathbf{R_L}$ values:

$\mathbf{R_L}$	330 Ω	560 Ω	1.2 kΩ
$\mathbf{V_{Lpeak}}$			
$\mathbf{V_{LDC}}$			

3. Add a 22 μF capacitor in parallel with $\mathbf{R_L}$ (<u>make sure that capacitor polarity matches the $\mathbf{V_L}$ polarity</u>).



Measure and/or calculate the peak amplitude of v_L, peak-to-peak ripple voltage, DC value of v_L, and the DC load current for the three $\mathbf{R_L}$ values used previously. You can calculate the average DC load voltage, $\mathbf{V_{LDC}}$, using equation [6].

R_L	330 Ω	560 Ω	1.2 kΩ
V_{Lpeak}			
V_{rplPP}			
V_{LDC} measured			
V_{LDC} calculated			
I_{LDC} calculated			

3.a) What is the load regulation of this circuit for $R_L = \infty$ and R_L = 330 Ω? Use the V_{LDC} measured for R_L = 560 Ω as the nominal voltage.

3.b) Calculate the ripple factor for the three R_L values.

3.c) Explain the effect of load resistance on the ripple voltage.

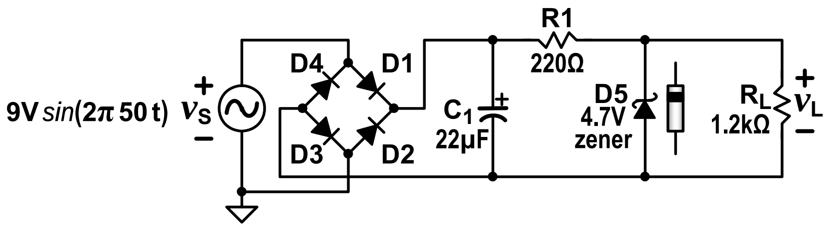
4. Use **R_L = 330 Ω**, and connect another **22 μF** capacitor in addition to **C1** in parallel with **R_L**. Copy the first column data from above and measure and/or calculate the peak amplitude of v_L, peak-to-peak ripple voltage, DC value of v_L, and the DC load current for two capacitors in the right column.

Filter Capacitor	22 μF	22+22 μF
V_{Lpeak}		
V_{rplPP}		
V_{LDC} measured		
V_{LDC} calculated		
I_{LDC} calculated		

4.a) What is the load regulation with two 22 μF capacitors?

4.b) Explain the effect of filter capacitance on the ripple voltage.

5. Turn off the function generator and build the following circuit. Make sure that the zener diode cathode is on the positive voltage side as shown below before you turn on the function generator again.



Measure and/or calculate the peak amplitude of v_L, peak-to-peak ripple voltage, DC value of v_L, and the DC load current for the three $\mathbf{R_L}$ values used previously.

R_L	330 Ω	560 Ω	1.2 kΩ
V_{Lpeak}			
V_{rplPP}			
V_{LDC} measured			
V_{LDC} calculated			
I_{LDC} calculated			

5.a) How can you determine when the zener diode is conducting?

5.b) Roughly measure the duty cycle of current through the zener diode and estimate the power dissipated on the zener diode for each R_L value.

5.c) Compare the results of capacitor-only and zener diode filter circuits. Explain the advantages and disadvantages of each filtering technique.