3. Diode, Rectifiers, and Power Supplies

Semiconductor diodes are active devices which are extremely important for various electrical and electronic circuits. Diodes are active non-linear circuit elements with non-linear voltage-current characteristics. Diodes are used in a wide variety of applications in communication systems (limiters, gates, clippers, mixers), computers (clamps, clippers, logic gates), radar circuits (phase detectors, gain-control circuits, power detectors, parameter amplifiers), radios (mixers, automatic gain control circuits, message detectors), and television (clamps, limiters, phase detectors, etc). The ability of diodes to allow the flow of current in only one direction is commonly exploited in these applications. Another common application of diodes is in rectifiers for power supplies.

In this chapter we will study some simple diodes and their application in rectifier circuits for power supplies. Three basic types of rectifier circuits will be studied. Rectifiers are mainly used in power supplies where an AC signal is to be converted to DC. The DC voltage is obtained by passing the rectifier's output through a filter to remove the ripple (AC components). Although, various types of filters (covered in the chapter on Frequency Response) can be used, in this chapter we will limit our analysis to the simplest type of filter using a capacitor.

The main learning objectives for this chapter are listed below.

Learning Objectives:

- Understand the voltage-current characteristics of a semiconductor diode
- Understand operation of half-wave and full-wave rectifier circuits
- Determination of output voltages and currents.
- Analyze the operation of rectifier circuit with capacitor filter
- Calculation of peak inverse voltage for rectifier circuits
- Study the application of diodes in power supply circuits

Recommended text for this section of the course:

(i) Allan R. Hambley, *Electrical Engineering Principles and Applications*, Chapter 10.

(ii) Giorgio Rizzoni, *Principles and Applications of Electrical Engineering*, Chapter 9.

3.1 Diode

Diodes allow electricity to flow in only one direction. Diodes are the electrical version of a valve and early diodes were actually called valves.

The schematic symbol of a diode is shown below. The arrow of the circuit symbol shows the direction in which the current can flow.

The diode has two terminals, a cathode and an anode as shown in Figure 1.
If a negative voltage is applied to the cathode and a positive voltage to the anode, the diode is forward biased and conducts. The diode acts nearly as a short circuit. If the polarity of the applied voltage is changed, the diode is reverse biased and does not conduct. The diode acts very much as an open circuit.
Finally, if the voltage v_D is more negative than the Reverse Breakdown voltage (also called the Zener voltage, V_Z), the diode conducts again, but in a reverse direction. The voltage versus current characteristics of a silicon diode is shown in Figure 2.

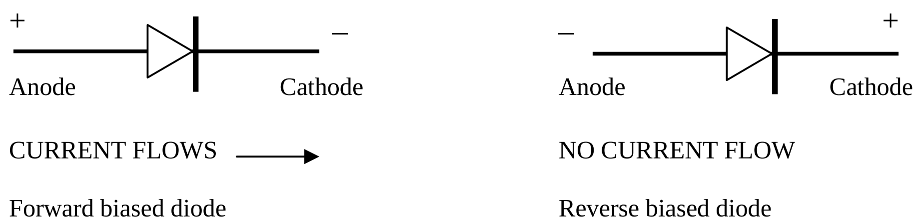

Figure 1: Diode operation

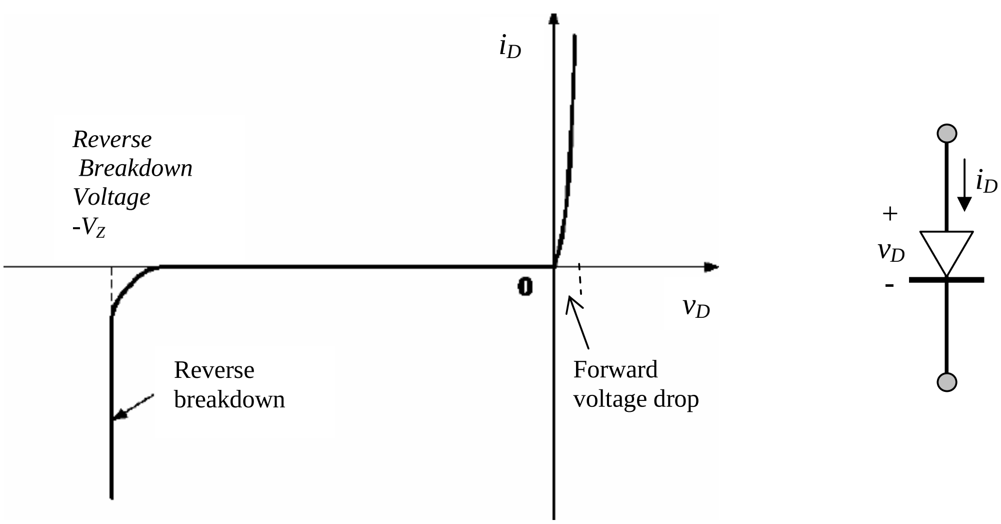

Figure 2: Voltage-current characteristics of a Silicon diode

3.1.1 Forward Voltage Drop

Electricity uses up a little energy pushing its way through the diode, rather like a person pushing through a door with a spring. This means that there is a small voltage across a conducting diode, it is called the **forward**

voltage drop and is about 0.7V for all normal diodes which are made from silicon. The forward voltage drop of a diode is almost constant whatever the current passing through the diode so they have a very steep characteristic (refer to current-voltage graph).

3.1.2 Reverse Voltage

Though we say that a diode does not conduct in the reverse direction, there are limits to the reverse electrical pressure that can be applied. The manufacturers of diodes specify a **peak inverse voltage** (PIV) that the diode can safely withstand. If this is exceeded, the diode will fail and allow a large current to flow in the reverse direction. This voltage is also called the Reverse Breakdown voltage.

3.1.3 Ideal Diode

For most practical applications, the operating voltage is high, and the forward voltage drop is negligible in comparison. The voltage-current characteristics of a diode (shown in figure 3) suggest that we can use the following model of an ideal diode for all practical purposes (i.e., ignoring the forward voltage drop).

The ideal diode acts as a short circuit for forward currents and as an open circuit with reverse voltage applied.

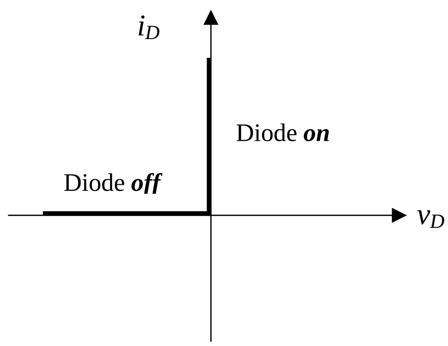

Figure 3: Ideal characteristics

3.2 Diode Rectifier Circuits

One of the important applications of a semiconductor diode is in rectification of AC signals to DC. Diodes are very commonly used for obtaining DC voltage supplies from the readily available AC voltage.

There are many possible ways to construct rectifier circuits using diodes. The three basic types of rectifier circuits are:

- The Half Wave Rectifier
- The Full Wave Rectifier
- The Bridge Rectifier

In the remaining sections of this chapter, we will study the operation of these circuits in detail, and study their application in power supply circuits.

3.3 Half-wave Rectifier

The easiest rectifier to understand is the half wave rectifier. A simple half-wave rectifier using an ideal diode and a load is shown in Figure 4.

Circuit operation

Let's look at the operation of this single diode rectifier when connected across an alternating voltage source v_s.

Since the diode only conducts when the anode is positive with respect to the cathode, current will flow only during the positive half cycle of the input voltage.

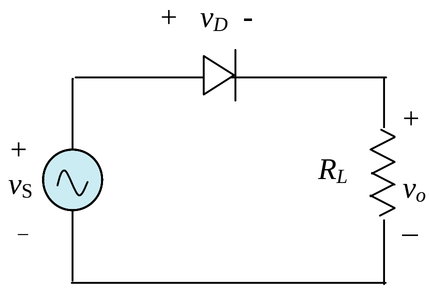

Figure 4: Simple half-wave rectifier circuit

The supply voltage is given by:

$$v_s = V_m \sin \omega t \quad (1)$$

where ω (= 2πf = 2π/T) is the angular frequency in rad/s.

We are interested in obtaining DC voltage across the "load resistance" R_L.

During the positive half cycle of the source, the ideal diode is forward biased and operates as a closed switch. The source voltage is directly connected across the load. During the negative half cycle, the diode is reverse biased and acts as an open switch. The source voltage is disconnected from the load. As no current flows through the load, the load voltage v_o is zero. Both the load voltage and current are of one polarity and hence said to be rectified. The waveforms for source voltage v_S and output voltage v_o are shown in figure 5.

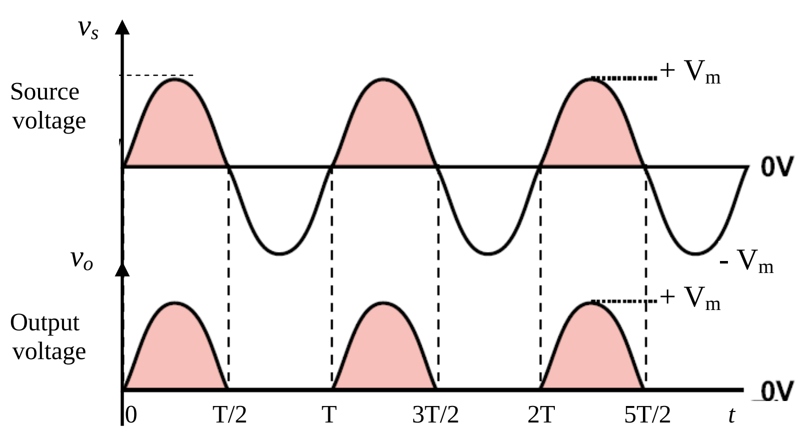

Figure 5: Source and output voltages

We notice that the output voltage varies between the peak voltage V_m and zero in each cycle. This variation is called "ripple", and the corresponding voltage is called the peak-to-peak ripple voltage, V_{p-p}.

Average load voltage and current

If a DC voltmeter is connected to measure the output voltage of the half-wave rectifier (i.e., across the load resistance), the reading obtained would be the average load voltage V_{ave}, also called the DC output voltage. The meter averages out the pulses and displays this average.

$$V_{ave} = \int_0^T v_o.dt = \int_0^{T/2} V_m \sin(\omega t).dt + \int_{T/2}^{T} 0.dt$$
$$= \frac{2V_m}{\omega T}\left[\cos 0 - \cos\frac{\omega T}{2}\right] = \frac{2V_m}{2\pi}[\cos 0 - \cos\pi]$$

Or, $V_{ave} = \dfrac{V_m}{\pi}$ (2)

The output voltage waveform and average voltage are shown in figure 6.

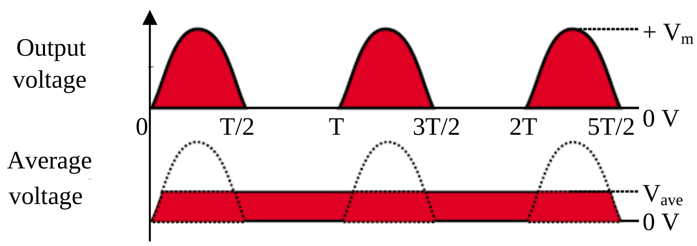

Figure 6: Output voltage and average voltage for half-wave rectifier

The output v_o may be viewed as a DC voltage plus a ripple voltage. As we can see, the output has a large amount of ripple.

Average Load Current

Just as we can convert a peak voltage to average voltage, we can also convert a peak current to an average current. The value of the average load current is the value that would be measured by a DC ammeter.

$$I_L = \frac{V_{ave}}{R_L} \quad (3)$$

where I_L is the average current passing through the load resistance.

Peak Inverse Voltage

The maximum amount of reverse bias that a diode will be exposed to is called the peak inverse voltage or PIV. For the half wave rectifier, the value of PIV is:

$$PIV = V_m \quad (4)$$

The reasoning for the above equation is that when the diode is reverse biased, there is no voltage across the load. Therefore, all of the secondary voltage (V_m) appears across the diode. The PIV is important because it determines the minimum allowable value of reverse voltage for any diode used in the circuit.

How can we use the load-line method for analyzing diode circuits? How is the load line and the operating point determined?

Example 1

A 50Ω load resistance is connected across a half wave rectifier. The input supply voltage is 230V (rms) at 50 Hz. Determine the DC output (average) voltage, peak-to-peak ripple in the output voltage (V_{p-p}), and the output ripple frequency (f_r).

Solution:

The peak amplitude of the source voltage can be calculated as: $V_m = \sqrt{2} \times 230 = 325.3V$

Output DC voltage:

$$V_{ave} = \frac{V_m}{\pi} = \frac{325.3}{\pi} = 103.5V$$

The peak-to-peak ripple voltage is the difference between the maximum and the minimum in the v_o waveform.

Therefore, $V_{p-p} = V_m - 0 = 325.3V$

Percentage ripple = (V_{p-p}/V_{ave}) x 100 = 314%

The ripple is at the supply frequency of 50 Hz.
Hence $f_r = 50\ Hz$

We notice that the "percentage ripple" is 314%, which is very large, and undesirable. This ripple can be reduced by adding a capacitor across the load resistor. The capacitor acts to filter (reduce) the ripple voltage, as we will see later.

3.4 Diode rectifier for power supply

The purpose of a power supply is to take electrical energy in one form and convert it into another. There are many types of power supply. Most are designed to convert high voltage AC mains electricity to a suitable low voltage supply for electronics circuits and other devices such as computers, fax machines and telecommunication equipment. In Singapore, supply from 230V, 50Hz AC mains is converted into smooth DC using AC-DC power supply.

A power supply can by broken down into a series of blocks, each of which performs a particular function. A transformer first steps down high voltage AC to low voltage AC. A rectifier circuit is then used to convert AC to DC. This DC, however, contains ripples, which can be smoothened by a filter circuit. Power supplies can be 'regulated' or 'unregulated'. A regulated power supply maintains a constant DC output voltage through 'feedback action'. The output voltage of an unregulated supply, on the other hand, will not remain constant. It will vary depending on varying operating conditions, for example when the magnitude of input AC voltage changes.

Main components of a regulated supply to convert 230V AC voltage to 5V DC are shown below.

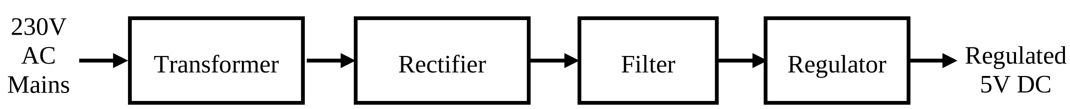

Figure 7: Block diagram of a regulated power supply

Power supplies are designed to produce as little ripple voltage as possible, as the ripple can cause several problems. For Example

- In audio amplifiers, too much ripple shows up as an annoying 50 Hz or 100 Hz audible hum.
- In video circuits, excessive ripple shows up as "hum" bars in the picture.
- In digital circuits it can cause erroneous outputs from logic circuits.

3.5 Half-wave Rectifier with Capacitor Filter

The capacitor is the most basic filter type and is the most commonly used. The half-wave rectifier for power supply application is shown below. A capacitor filter is connected in parallel with the load. The rectifier circuit is supplied from a transformer.

Circuit operation

The operation of this circuit during positive half cycle of the source voltage is shown in figure 8. During the positive half cycle, diode D1 will conduct, and the capacitor charges rapidly. As the input starts to go negative, D1 turns off, and the capacitor will slowly discharge through the load (figure 9).

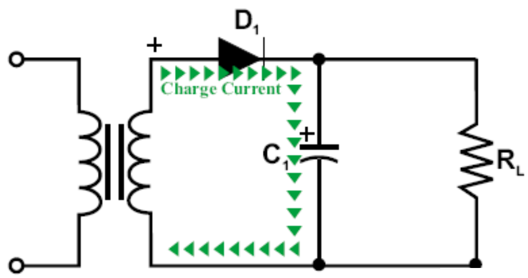

Figure 8: Half wave rectifier with capacitor filter – positive half cycle

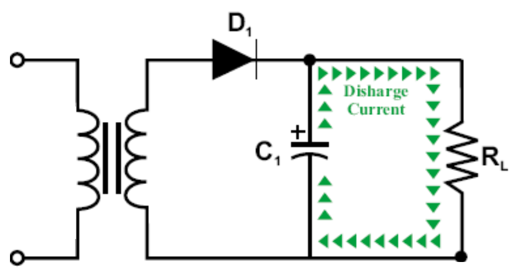

Figure 9: Half wave rectifier with capacitor filter – negative half cycle

Using the previous half wave rectifier as an example, figure 10 examines what is happening with our filter.

(a) Unfiltered output from the half wave rectifier

(b) When the next pulse does arrive, it charges the capacitor back to full charge as shown on the right. The thick line shows the charge – discharge waveform at the capacitor.

(c) The load sees a reasonably constant DC voltage now, with a ripple voltage on top of it.

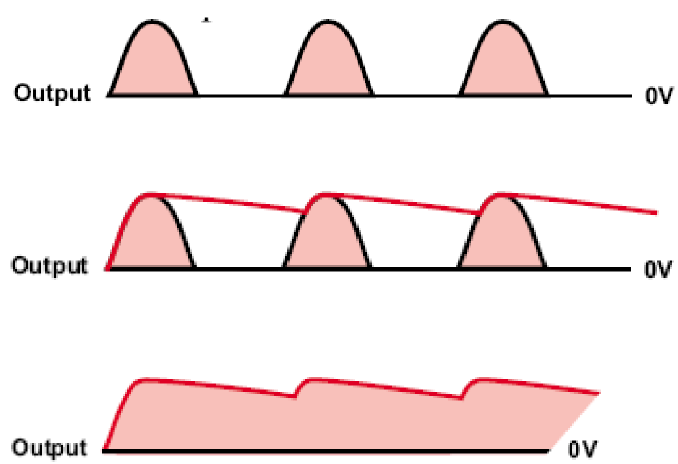

Figure 10

The operation can be analyzed in detail using figure 11.

During each positive half cycle, the capacitor charges during the interval t_1 to t_2. During this interval, the diode will be forward biased. Due to this charging, the voltage across the capacitor v_o will be equal to the AC peak voltage V_m on the secondary side of the transformer at t_2 (assuming diode forward voltage drop is zero).

The capacitor will supply current to load resistor R_L during time interval t_2 to t_3. During this interval, diode will be reverse biased since the AC voltage is less than the output voltage v_o. Due to the large energy stored in the capacitor, the capacitor voltage will not reduce much during t_2 to t_3, and the voltage v_o will remain close to the peak value. As can be seen, addition of the capacitor results in much better quality output voltage.

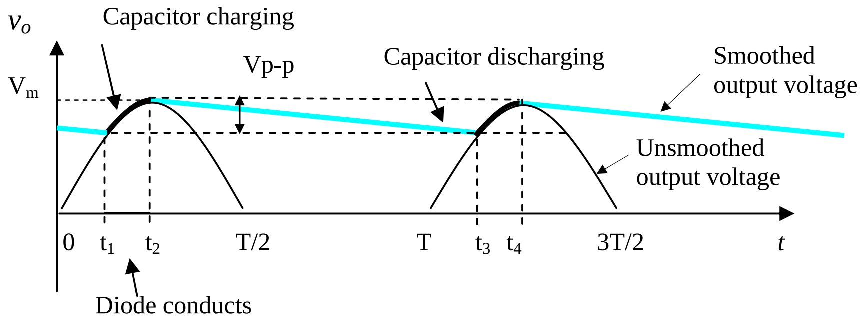

Figure 11: Output voltage waveform of half-wave rectifier with capacitor filter

Average load voltage

In practical applications, a very large capacitor is used so that the output voltage is close to the peak value. The average voltage (also called DC output voltage) across the load can therefore be approximated to:

$$V_{ave} \cong V_m \tag{5}$$

Calculation of capacitance

The voltage waveforms show a small AC component called "ripple" present in the output voltage. This ripple can be minimized by choosing the largest capacitance value that is practical. The capacitor is typically "electrolytic" type, and is very large (several hundreds or even thousands of microfarads). We can calculate the required value of the filter capacitor as follows.

The charge removed from the capacitor during the discharge cycle (i.e., t_2 to t_3) is:

$$\Delta Q \cong I_L T \tag{6}$$

Where I_L is the average load current and T is the period of the AC voltage. As the interval t_1 to t_2 is very small, the discharge time can be approximated to T.

If $V_{p\text{-}p}$ is the peak-to-peak ripple voltage, and C is the capacitance, the charge removed from the capacitor can also be expressed as:

$$\Delta Q = V_{p-p}\, C \tag{7}$$

From these two equations, capacitance C can be calculated as:

$$C = \frac{I_L T}{V_{p-p}} \text{ Farads} \tag{8}$$

What will be the peak inverse voltage for this diode?

Our goal is to produce a constant dc output voltage. The filter capacitor will remove most of the variations in our rectifier output waveform.

The amount of ripple voltage left by a given filter depends on the three things:

- Type of rectifier (half or full wave)
- The capacity of the filter capacitor
- The load resistance

How does changing the load resistance affect ripple?

Example 2

In the circuit of example 1, a 10000μF filter capacitor is added across the load resistor. The voltage across the secondary terminals of the transformer is 230V (rms). Determine the DC output voltage (i.e. average voltage), load current, peak-to-peak ripple in the output voltage, and the output ripple frequency.

Solution

DC output voltage, $V_{ave} \cong V_m = 325.3$ V

The load current is given by $I_L = \frac{V_{ave}}{R_L} \cong \frac{325.3}{50} = 6.51A$

This current discharges the capacitor during the interval t_2 to t_3.

The time period of the AC voltage = 20 ms (for 50 Hz frequency)

Thus, the charge supplied by the capacitor to the load resistance during this interval will be:

$$\Delta Q = I_L T = 6.51 \times 20 \times 10^{-3} = 0.1302\, Coulomb$$

The peak-to-peak ripple voltage: $V_{p-p} = \frac{\Delta Q}{C} = \frac{0.1302}{10000 \times 10^{-6}} = 13.02V$

The larger the capacitor value, the smaller the ripple.

Notice that the ripple voltage is now only 4%, compared to 314% when the capacitor is not used.

The ripple frequency is same as before (50 Hz).

3.6 The Full-Wave Rectifier

The full wave rectifier consists of two diodes and a resister as shown in Figure 12.

The transformer has a centre-tapped secondary winding. This secondary winding has a lead attached to the centre of the winding. The voltage from the centre tap to either end terminal on this winding is equal to one half of the total voltage measured end-to-end.

Circuit Operation

Figure 12 shows the operation during the positive half cycle of the full wave rectifier. Note that diode D1 is forward biased and diode D2 is reverse biased. Note the direction of the current through the load.

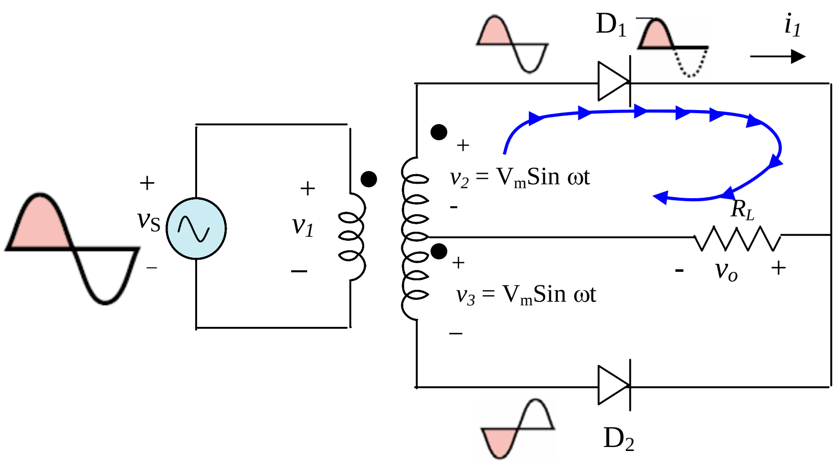

Figure 12: Full-wave rectifier- Circuit operation during positive half cycle

During the negative half cycle, (figure 13) the polarity reverses. Diode D2 is forward biased and diode D1 is reverse biased. Note that the direction of current through the load has not changed even though the secondary voltage has changed polarity. Thus another positive half cycle is produced across the load.

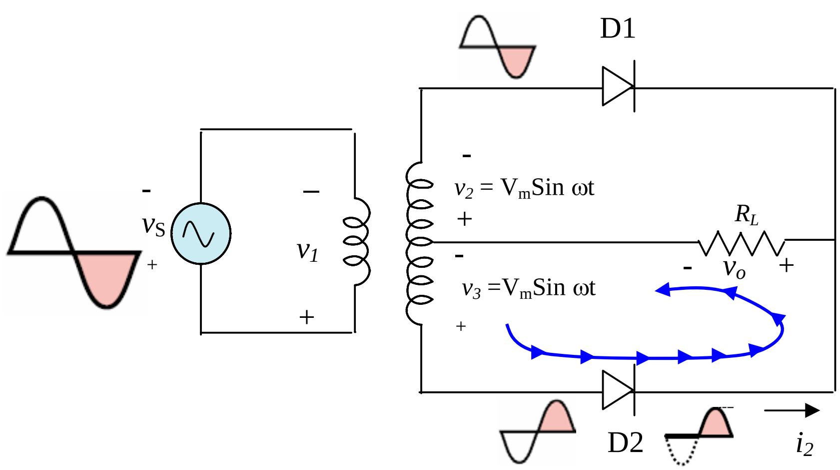

Figure 13: Full-wave rectifier – circuit operation during negative half cycle

Calculating Load Voltage and Currents

Using the ideal diode model, the peak load voltage for the full wave rectifier is V_m. The full wave rectifier produces twice as many output pulses as the half wave rectifier. This is the same as saying that the full wave rectifier has twice the output frequency of a half wave rectifier. For this reason, the average load voltage (i.e. DC output voltage) is found as

$$V_{ave} = \frac{2V_m}{\pi} \tag{9}$$

Figure 14 below illustrates the average dc voltage for a full wave rectifier.

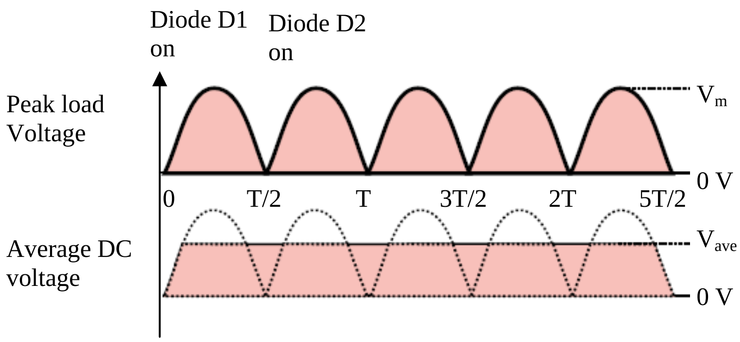

Figure 14: Average DC Voltage for a Full Wave Rectifier

Peak Inverse Voltage

When one of the diodes in a full-wave rectifier is reverse biased, the peak voltage across that diode will be approximately equal to V_m. This point is illustrated in figure 13. With the polarities shown, D1 is conducting and D2 is reverse biased. Thus the cathode of D1 will be at V_m. Since this point is connected directly to the cathode of D2, its cathode will also be V_m. With $-V_m$ applied to the anode of D2, the total voltage across the diode D2 is $2V_m$. Therefore, the maximum reverse voltage across either diode will be twice the peak load voltage.

$$PIV = 2V_m \tag{10}$$

<u>**Example 3**</u>

In the full-wave rectifier circuit of figure 12, the transformer has a turns ratio of 1:2. The transformer primary winding is connected across an AC source of 230V (rms), 50 Hz. The load resistor is 50Ω. For this circuit, determine the DC output voltage, peak-to-peak ripple in the output voltage, and output ripple frequency.

Solution

The rms value of secondary voltage = 460 V

RMS value of v_2 (and v_3) = 230 V

Peak value of v_2 (and v_3): $V_m = \sqrt{2} \times 230 = 325.3V$

DC Output voltage (i.e. average load voltage): $V_{ave} = \frac{2V_m}{\pi} = 207V$

The peak-to-peak ripple voltage can be calculated as:

$V_{p-p} = V_m - 0 = 325.3V$

Ripple frequency = 100 Hz, which is twice the AC supply frequency of 50 Hz.

Though the ripple is still very large, the percentage ripple has come down from 314% (for the half-wave rectifier in example 1) to 157%. This ripple can be reduced by adding a capacitor in the circuit, as we will see in the next section.

3.7 Full-Wave Rectifier with Capacitor filter

Similar to the half-wave rectifier, smoothing is performed by a large value capacitor connected across the load resistance (as shown in figure 15) to act as a reservoir, supplying current to the output when the varying DC voltage from the rectifier is falling.

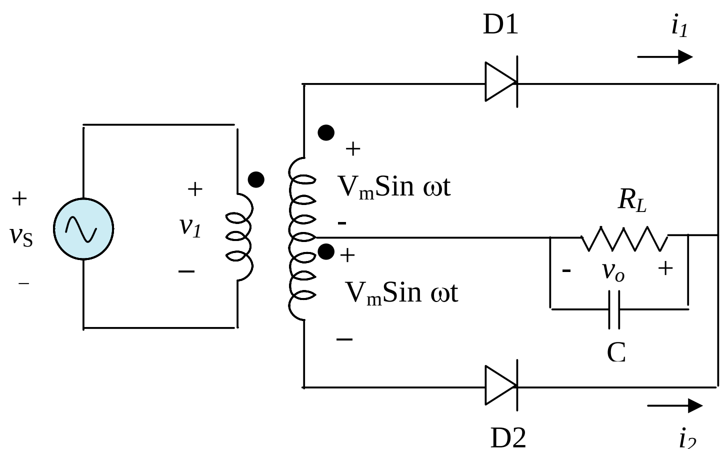

Figure 15: Full-wave rectifier with filter capacitor

The diagram below shows the unsmoothed varying DC (thin line) and the smoothed DC (thick line). The capacitor charges quickly near the peak of the varying DC, and then discharges as it supplies current to the output.

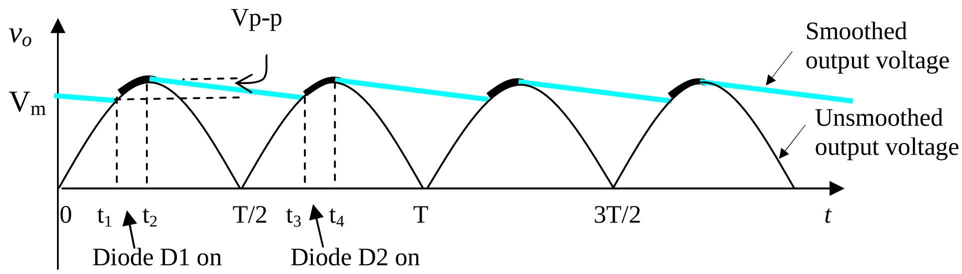

Figure 16: Load voltage waveform for the full-wave rectifier with filter capacitor

Note that smoothing significantly increases the average DC voltage to almost the peak value. However, smoothing is not perfect due to the capacitor voltage falling a little as it discharges, giving a small **ripple voltage**. For many circuits a ripple which is 10% of the supply voltage is satisfactory and the equation below gives the required value for the smoothing capacitor. In the full-wave circuit, the capacitor discharges for only a half-cycle before being recharged. Hence the capacitance required is only half as much in the full-wave circuit as for the half-wave circuit.

$$C = \frac{I_L T}{2V_{p-p}} \qquad (10)$$

Derive the above expression for capacitance as an exercise.

3.8 The Full Wave Bridge Rectifier

In many power supply circuits, the bridge rectifier (Figure 17) is used. The bridge rectifier produces almost double the output voltage as a full wave center-tapped transformer rectifier using the same secondary voltage. The advantage of using this circuit is that no center-tapped transformer is required.

Basic Circuit Operation

During the positive half cycle (Figure 17) , both D3 and D1 are forward biased. At the same time, both D2 and D4 are reverse biased. Note the direction of current flow through the load.

During the negative half cycle (Figure 18) D2 and D4 are forward biased and D1 and D3 are reverse biased. Again note that current through the load is in the same direction although the secondary winding polarity has reversed.

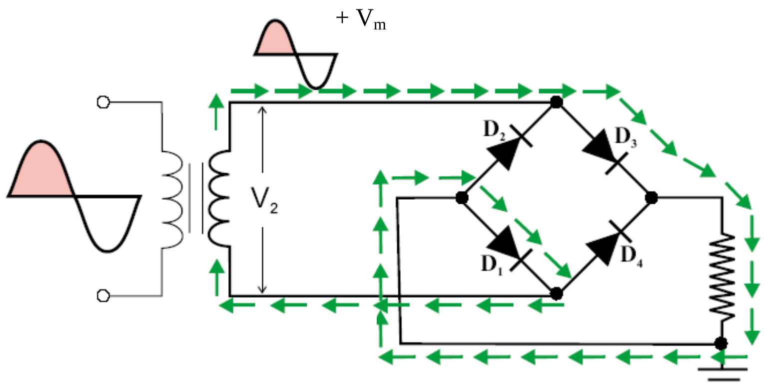

Figure 17: Operation during positive half cycle

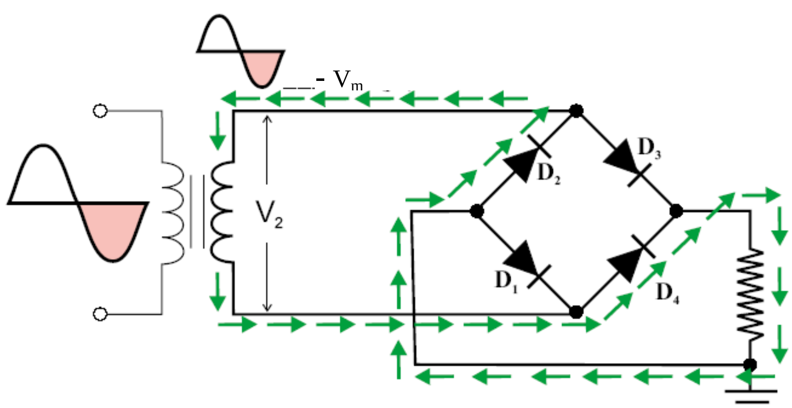

Figure 18: Operation during negative half cycle

Peak Inverse Voltage

In order to understand the Peak Inverse Voltage across each diode, look at figure 19 below. It is a simplified version of figure 17 showing the circuit conditions during the positive half cycle. The load and ground connections are removed because we are concerned with the diode conditions only. In this circuit, diodes D1 and D3 are forward biased and act like closed switches. They can be replaced with wires. Diodes D2 and D4 are reverse biased and act like open switches.

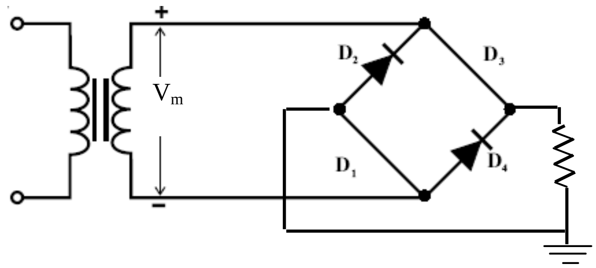

Figure 19: Equivalent bridge rectifier circuit during positive half cycle

The circuit of figure 19 is redrawn below. We can see that both diodes are reverse biased, in parallel, and directly across the secondary winding. The peak inverse voltage is therefore equal to V_m.

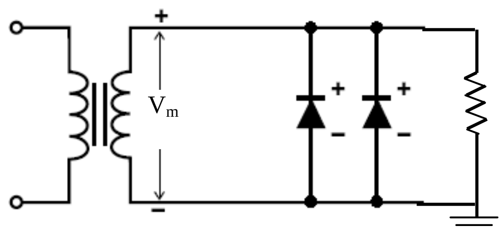

Figure 20: Simplified circuit

Therefore, Peak inverse voltage = V_m

3.9 Full Wave Bridge Rectifier With Capacitor Filter

The voltage obtained across the load resistor of the full-wave bridge rectifier described above has a large amount of ripple. A capacitor filter may be added to smoothen the ripple in the output, as shown below.

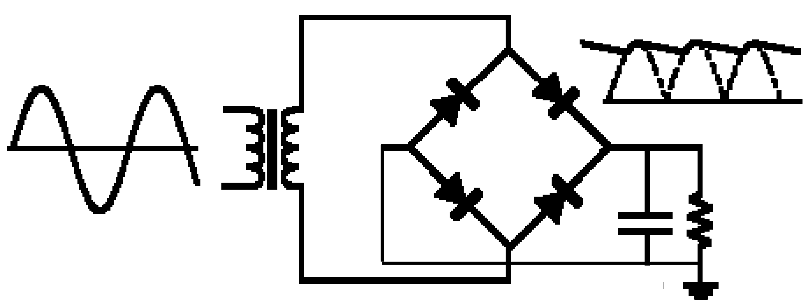

Figure 21: Full wave Bridge rectifier with capacitor filter

The rectifier circuits discussed above can be used to charge batteries and to convert AC voltages into constant DC voltages. Full-wave and bridge rectifier are more commonly used than half-wave rectifier.