Table of Contents

1.1   Introduction

- In electric circuit we have to provide a path through which charge can flow easily by the movements of electrons.

1.1.1   Conductors

- Materials through which charge flows readily are called conductors.
- A conductor has a very low resistance to the flow of charge.
- Ex. Silver, gold, copper, aluminum and such metals.
- Copper is used mostly for the conductive paths on electric circuit boards and for the fabrication of electric wires.

1.1.2   Insulators

- Materials that do not allow charge to move easily. Electric current cannot be made to flow through it.
- An insulator has very high resistance to the flow of charge.
- Ex: glass, plastic, ceramics and rubber.
- Insulating materials wrapped around the conducting core of the wire.

1.1.3   Semiconductors

- Semiconductors lie in the middle between conductors and insulators
- Semiconductor has moderate resistance to the flow of charge.
- Ex. Elemental semiconductors are Silicon, germanium whereas gallium arsenide is an example of compound semiconductors which are developed.

1.1.4   P-Type Semiconductors

- Silicon that has been doped with a trivalent impurities like aluminum, boron and gallium is called a p-type semiconductor, where the p stands for positive.
- Since holes outnumber free electrons, the holes are referred to as the majority carriers and the free electrons are known as the minority carriers.

1.1.5   N-Type Semiconductors

- Silicon that has been doped with a trivalent impurities like arsenic, antimony and phosphorus is called an n-type semiconductor, where the n stands for negative.
- Since free electrons outnumber the holes in an n-type semiconductor, the free electrons are called as the majority carriers and the holes are called as the minority carriers.
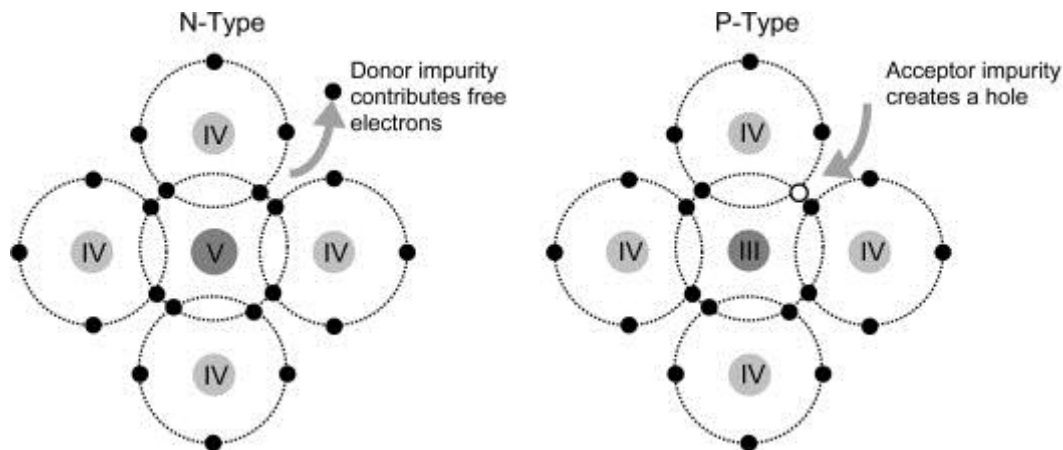
Figure-1 N-Type and P-Type Semiconductor's Atomic Level Arrangements

1.2   The Diode

- By itself, a piece of n-type semiconductor is about as useful as a carbon resistor; the same can be said for a p-type semiconductor.
- But when a manufacturer dopes a crystal so that one-half of it is p-type and the other half is n-type, something new comes into existence.
- The border between p-type and n-type is called the pn junction.
- The pn junction has led to all kinds of inventions, including diodes, transistors, and integrated circuits.
- Understanding the pn junction enables you to understand all kinds of semiconductor devices.

1.2.1   The Unbiased Diode

- As discussed in the preceding section, each trivalent atom in a doped silicon crystal produces one hole.
- For this reason, we can visualize a piece of p-type semiconductor as shown on the left side of Figure-2. Each circled minus sign is the trivalent atom, and each plus sign is the hole in its valence orbit.
- Similarly, we can visualize the pentavalent atoms and free electrons of an n-type semiconductor as shown on the right side of Figure-2. Each circled plus sign represents a pentavalent atom, and each minus sign is the free electron it contributes to the semiconductor.
- Notice that each piece of semiconductor material is electrically neutral because the number of pluses and minuses are equal.
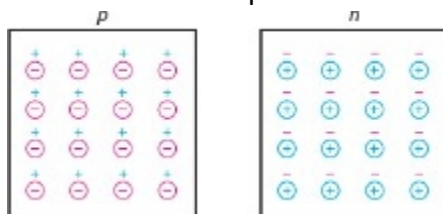
Figure-2 Two Types of Semiconductor
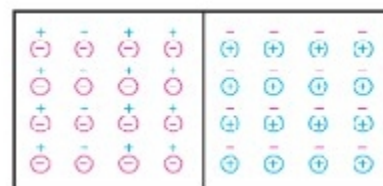
Figure-3 The P-N Junction

- A manufacturer can produce a single crystal with p-type material on one side and n-type on the other side, as shown in Figure-3.

- The junction is the border where the p-type and the n-type regions meet, and junction diode is another name for a pn crystal.
- The word diode is a contraction of two electrodes, where *di* stands for "two."

1.2.2 The Depletion Layer

- Because of their repulsion for each other, the free electrons on the n side of Figure-3 tend to diffuse (spread) in all directions.
- Some of the free electrons diffuse across the junction. When a free electron enters the p region, it becomes a minority carrier.
- With so many holes around it, this minority carrier has a short lifetime.
- Soon after entering the p region, the free electron recombines with a hole.
- When this happens, the hole disappears and the free electron becomes a valence electron.
- Each time an electron diffuses across a junction, it creates a pair of ions.
- When an electron leaves the n side, it leaves behind a pentavalent atom that is short one negative charge; this pentavalent atom becomes a positive ion.
- After the migrating electron falls into a hole on the p side, it makes a negative ion out of the trivalent atom that captures it. Figure-4 shows these ions on each side of the junction.
- The circled plus signs are the positive ions, and the circled minus signs are the negative ions.
- The ions are fixed in the crystal structure because of covalent bonding, and they cannot move around like free electrons and holes.
- Each pair of positive and negative ions at the junction is called a dipole.
- The creation of a dipole means that one free electron and one hole have been taken out of circulation.
- As the number of dipoles builds up, the region near the junction is emptied of carriers. We call this charge-empty region the depletion layer (see Figure-5).

1.2.3 Barrier Potential

- Each dipole has an electric field between the positive and negative ions. Therefore, if additional free electrons enter the depletion layer, the electric field tries to push these electrons back into the n region.
- The strength of the electric field increases with each crossing electron until equilibrium is reached.
- To a first approximation, this means that the electric field eventually stops the diffusion of electrons across the junction.
- In Figure-4, the electric field between the ions is equivalent to a difference of potential called the barrier potential.
- At 25°C, the barrier potential equals approximately 0.3 V for germanium diodes and 0.7 V for silicon diodes.
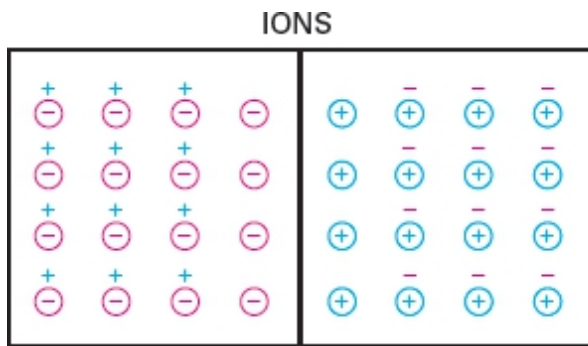
Figure-4 Creation of ions at junction　　　　　**Figure-5 Depletion layer**
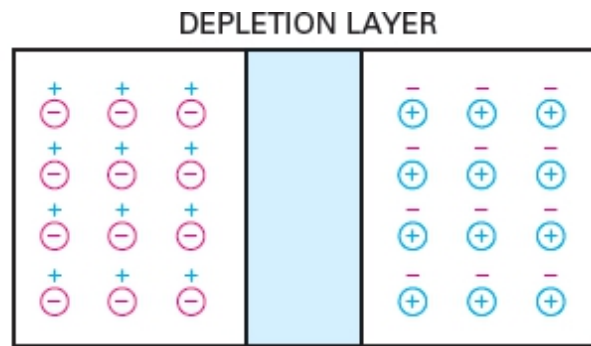
1.2.4 Forward Bias

- Figure-6 shows a dc source across a diode. The negative source terminal is connected to the n-type material, and the positive terminal is connected to the p-type material. This connection produces what is called forward bias.
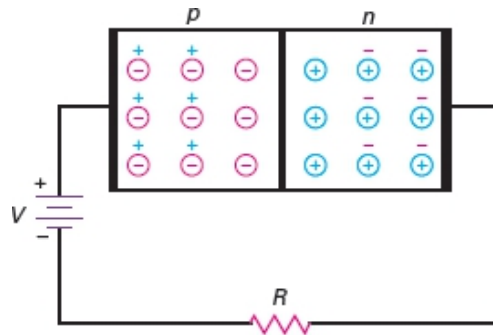
Figure-6 Forward bias

1.2.4.1 Flow of Free Electrons

- In Figure-6, the battery pushes holes and free electrons toward the junction.
- If the battery voltage is less than the barrier potential, the free electrons do not have enough energy to get through the depletion layer.
- When they enter the depletion layer, the ions will push them back into the n region. Because of this, there is no current through the diode.
- When the dc voltage source is greater than the barrier potential, the battery again pushes holes and free electrons toward the junction. This time, the free electrons have enough energy to pass through the depletion layer and recombine with the holes.
- If you visualize all the holes in the p region moving to the right and all the free electrons moving to the left, you will have the basic idea.
- Somewhere in the vicinity of the junction, these opposite charges recombine. Since free electrons continuously enter the right end of the diode and holes are being continuously created at the left end, there is a continuous current through the diode.

1.2.4.2 The Flow of One Electron

- Let us follow a single electron through the entire circuit.

- After the free electron leaves the negative terminal of the battery, it enters the right end of the diode. It travels through the n region until it reaches the junction.
- When the battery voltage is greater than 0.7 V, the free electron has enough energy to get across the depletion layer.
- Soon after the free electron has entered the p region, it recombines with a hole.
- In other words, the free electron becomes a valence electron. As a valence electron, it continues to travel to the left, passing from one hole to the next until it reaches the left end of the diode.
- When it leaves the left end of the diode, a new hole appears and the process begins again. Since there are billions of electrons taking the same journey, we get a continuous current through the diode.
- A series resistor is used to limit the amount of forward current.

1.2.4.3 What to Remember?

- Current flows easily in a forward-biased diode. As long as the applied voltage is greater than the barrier potential, there will be a large continuous current in the circuit.
- In other words, if the source voltage is greater than 0.7 V, a silicon diode allows a continuous current in the forward direction.

1.2.5 Reverse Bias

- Turn the dc source around and you get Figure-7. This time, the negative battery terminal is connected to the p side and the positive battery terminal to the n side.
- This connection produces what is called reverse bias.
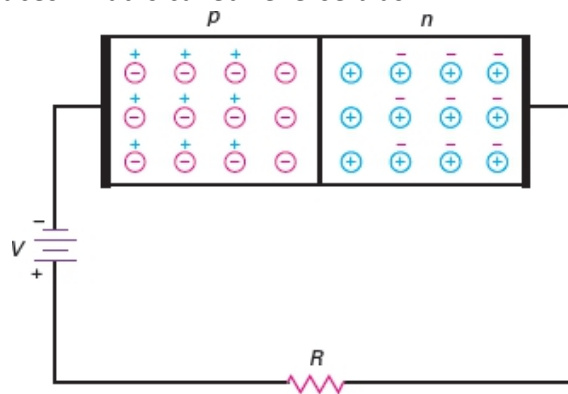
Figure-7 Reverse bias

1.2.5.1 Depletion Layer Widens

- The negative battery terminal attracts the holes, and the positive battery terminal attracts the free electrons. Because of this, holes and free electrons flow away from the junction. Therefore, the depletion layer gets wider.
- How wide does the depletion layer get in Figure-8?
- When the holes and electrons move away from the junction, the newly created ions increase the difference of potential across the depletion layer. The wider the depletion layer, the greater the difference of potential.

- The depletion layer stops growing when its difference of potential equals the applied reverse voltage. When this happens, electrons and holes stop moving away from the junction.
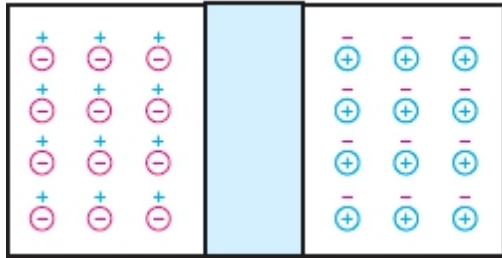
Figure-8 Depletion layer   **Figure-9 increasing reverse bias widens depletion layer**
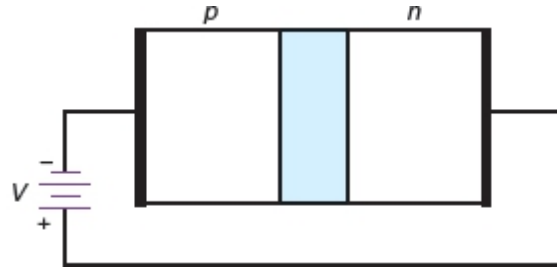
- Sometimes the depletion layer is shown as a shaded region like that of Figure-9. The width of this shaded region is proportional to the reverse voltage. As the reverse voltage increases, the depletion layer gets wider.

1.2.5.2   Minority-Carrier Current

- Is there any current after the depletion layer stabilizes? Yes. A small current exists with reverse bias. Recall that thermal energy continuously creates pairs of free electrons and holes. This means that a few minority carriers exist on both sides of the junction.
- Most of these recombine with the majority carriers. But those inside the depletion layer may exist long enough to get across the junction.
- When this happens, a small current flows in the external circuit.
- Figure 10 illustrates the idea. Assume that thermal energy has created a free electron and hole near the junction.
- The depletion layer pushes the free electron to the right, forcing one electron to leave the right end of the crystal. The hole in the depletion layer is pushed to the left. This extra hole on the p side lets one electron enter the left end of the crystal and fall into a hole.
- Since thermal energy is continuously producing electron-hole pairs inside the depletion layer, a small continuous current flows in the external circuit.
- The reverse current caused by the thermally produced minority carriers is called the saturation current. In equations, the saturation current is symbolized by I_S. The name saturation means that we cannot get more minority-carrier current than is produced by the thermal energy.
- In other words, increasing the reverse voltage will not increase the number of thermally created minority carriers.
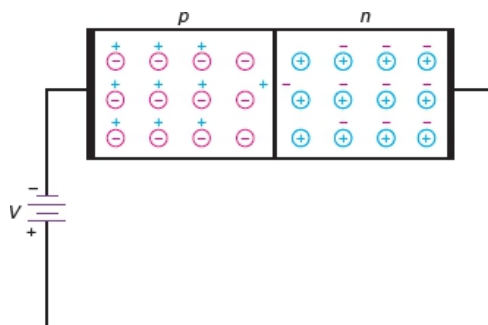
Figure-10 Thermal production of free electron and hole in depletion layer produces reverse minority-saturation current

1.2.5.3   Surface-Leakage Current

- Besides the thermally produced minority-carrier current, does any other current exist in a reverse-biased diode? Yes. A small current flows on the surface of the crystal. Known as the surface-leakage current, it is caused by surface impurities and imperfections in the crystal structure.

1.2.5.4   What to Remember

- The reverse current in a diode consists of a minority-carrier current and a surface-leakage current.
- In most applications, the reverse current in a silicon diode is so small that you don't even notice it.
- The main idea to remember is this: Current is approximately zero in a reverse-biased silicon diode.

1.3   V-I Characteristics of Diode

- An ordinary resistor is a linear device because the graph of its current versus voltage is a straight line.
- A diode is different. It is a nonlinear device because the graph of its current versus voltage is not a straight line.
- The reason is the barrier potential. When the diode voltage is less than the barrier potential, the diode current is small. When the diode voltage exceeds the barrier potential, the diode current increases rapidly.

1.3.1   The Schematic Symbol and Case Styles

- Figure-11 shows the pn structure and schematic symbol of a diode.
- The p side is called the anode, and the n side the cathode.
- The diode symbol looks like an arrow that points from the p side to the n side, from the anode to the cathode.
- Figure-12 shows some of the many typical diode case styles. Many, but not all, diodes have the cathode lead (K) identified by a colored band.
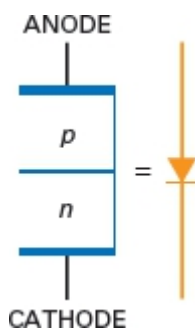
Figure-11 Schematic symbol

Figure-12 Diode case styles

1.3.2 Basic Diode Circuit

- Figure 13 shows a diode circuit. In this circuit, the diode is forward biased.
- How do we know? Because the positive battery terminal drives the p side through a resistor, and the negative battery terminal is connected to the n side. With this connection, the circuit is trying to push holes and free electrons toward the junction.
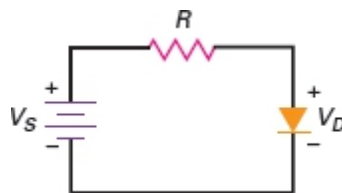
Figure-13 Forward Bias Circuit

1.3.3 The Forward Region

- Figure 13 is a circuit that you can set up in the laboratory. After you connect this circuit, you can measure the diode current and voltage.
- You can also reverse the polarity of the dc source and measure diode current and voltage for reverse bias.
- If you plot the diode current versus the diode voltage, you will get a graph that looks like Figure 14.
- For instance, when the diode is forward biased, there is no significant current until the diode voltage is greater than the barrier potential.
- On the other hand, when the diode is reverse biased, there is almost no reverse current until the diode voltage reaches the breakdown voltage. Then, avalanche produces a large reverse current, destroying the diode.
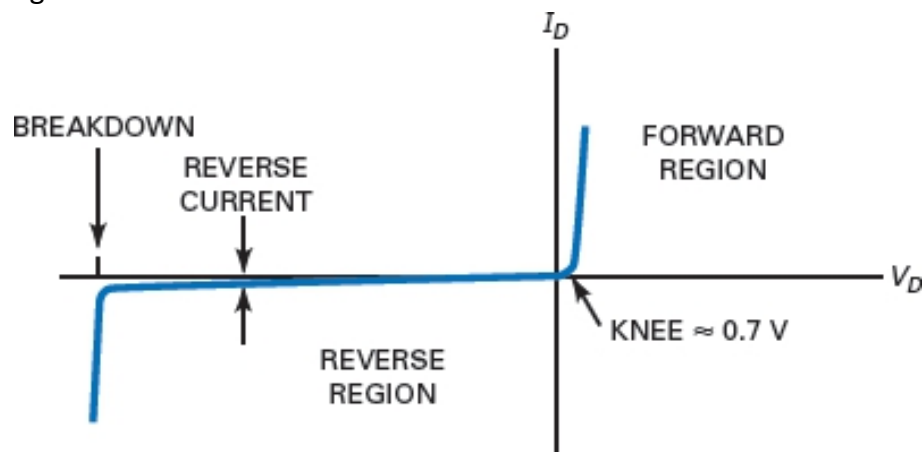
Figure-14 Diode Curve

1.3.4 Knee Voltage

- In the forward region, the voltage at which the current starts to increase rapidly is called the knee voltage of the diode. The knee voltage equals the barrier potential.
- Analysis of diode circuits usually comes down to determining whether the diode voltage is more or less than the knee voltage. If it's more, the diode conducts easily. If it's less, the diode conducts poorly.
- We define the knee voltage of a silicon diode as: ≈ .   ----------------------- **(1)**
- Even though germanium diodes are rarely used in new designs, you may still encounter germanium diodes in special circuits or in older equipment.
- For this reason, remember that the knee voltage of a germanium diode is approximately 0.3 V. This lower knee voltage is an advantage and accounts for the use of a germanium diode in certain applications.

1.3.5 Bulk Resistance

- Above the knee voltage, the diode current increases rapidly. This means that small increases in the diode voltage cause large increases in diode current.
- After the barrier potential is overcome, all that impedes the current is the ohmic resistance of the p and n regions.
- In other words, if the p and n regions were two separate pieces of semiconductor, each would have a resistance that you could measure with an ohmmeter, the same as an ordinary resistor.
- The sum of the ohmic resistances is called the bulk resistance of the diode.

$$\text{It is defined as: } R_B = R_P + R_N \text{------------------------------- (2)}$$

- The bulk resistance depends on the size of the p and n regions and how heavily doped they are. Often, the bulk resistance is less than $1 \, \Omega$.

1.3.6 Maximum DC Forward Current

- If the current in a diode is too large, the excessive heat can destroy the diode.
- For this reason, a manufacturer's data sheet specifies the maximum current a diode can safely handle without shortening its life or degrading its characteristics.
- The maximum forward current is one of the maximum ratings given on a data sheet. This current may be listed as I_{max}, $I_{F(max)}$, I_O, etc., depending on the manufacturer. For instance, a **1N456** has a maximum forward current rating of **135 mA**. This means that it can safely handle a continuous forward current of **135 mA**.

1.3.7 Power Dissipation

- You can calculate the power dissipation of a diode the same way as you do for a resistor. It equals the product of diode voltage and current.

$$\text{As a formula: } P_D = V_D \, I_D \text{------------------------------- (3)}$$

- The power rating is the maximum power the diode can safely dissipate without shortening its life or degrading its properties. In symbols, the definition is: $P_{max} = V_{max} \, I_{max}$ ------------------------------- **(4)**
- Where V_{max} is the voltage corresponding to I_{max}. For instance, if a diode has a maximum voltage and current of 1 V and 2 A, its power rating is 2 W.

Example 1

A diode has a power rating of 5 W. If the diode voltage is 1.2 V and the diode current is 1.75 A, what is the power dissipation? Will the diode be destroyed?

SOLUTION

$$P_D = (1.2\ V)\ (1.75\ A) = 2.1\ W$$

This is less than the power rating, so the diode will not be destroyed.

PRACTICE PROBLEM 1

Referring to Example 1, what is the diode's power dissipation if the diode voltage is 1.1 V and the diode current is 2 A?

1.4   The Ideal Diode

- Figure 15 shows a detailed graph of the forward region of a diode. Here you see the diode current I_D versus diode voltage V_D. Notice how the current is approximately zero until the diode voltage approaches the barrier potential.
- Somewhere in the vicinity of **0.6** to **0.7 V**, the diode current increases. When the diode voltage is greater than **0.8 V**, the diode current is significant and the graph is almost linear.
- Depending on how a diode is doped and its physical size, it may differ from other diodes in its maximum forward current, power rating, and other characteristics.
- If we need an exact solution, we have to use the graph of the particular diode.
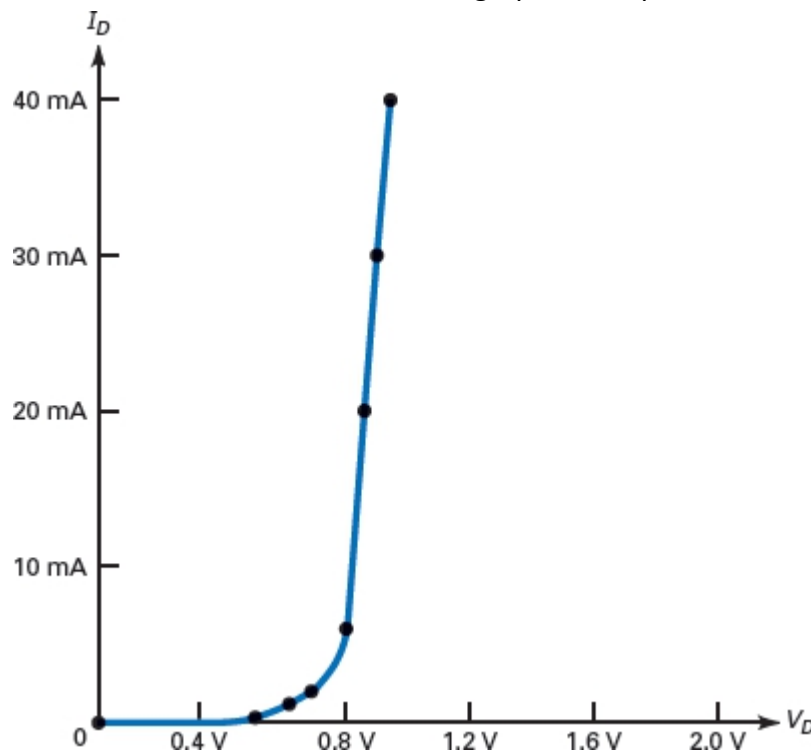

Figure-15 Graph of Forward Current

- Although the exact current and voltage points will differ from one diode to the next, the graph of any diode is similar to Figure 15.
- All silicon diodes have a knee voltage of approximately **0.7 V**.

- Most of the time, we do not need an exact solution. This is why we can and should use ***approximations*** for a diode. We will begin with the simplest approximation, called an ***ideal diode***. In the most basic terms, what does a diode do? It conducts well in the forward direction and poorly in the reverse direction.
- Ideally, a diode acts like a perfect conductor (zero resistance) when forward biased and like a perfect insulator (infinite resistance) when reverse biased.
- Figure 16 shows the current-voltage graph of an ideal diode. It echoes what we just said: zero resistance when forward biased and infinite resistance when reverse biased.
- It is impossible to build such a device, but this is what manufacturers would produce if they could.
- Is there any device that acts like an ideal diode? Yes. An ordinary switch has zero resistance when closed and infinite resistance when open.
- Therefore, an ideal diode acts like a switch that closes when forward biased and opens when reverse biased. Figure 17 summarizes the switch idea.
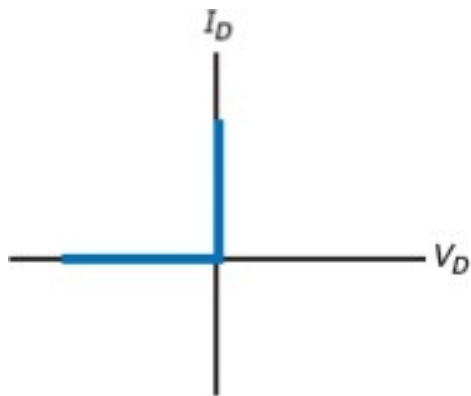
Figure-16 Ideal diode curve   **Figure-17 ideal diode acts like a switch**
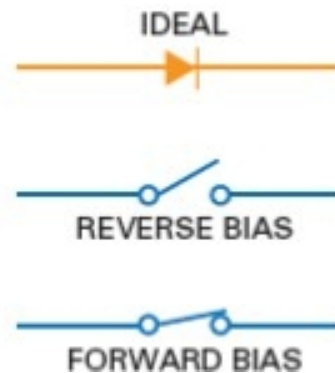
Example 2

Use the ideal diode to calculate the load voltage and load current in Figure 18.
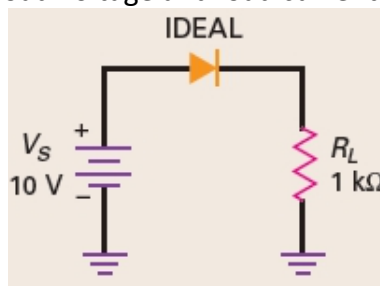
Figure-18

SOLUTION

Since the diode is forward biased, it is equivalent to a closed switch. Visualize the diode as a closed switch. Then, you can see that all of the source voltage appears across the load resistor:

$$V_L = 10 \text{ V}$$

With Ohm's law, the load current is:

$$= \quad / \quad \Omega =$$

PRACTICE PROBLEM 2

In above example, find the ideal load current if the source voltage is 5 V.

Example 3

Calculate the load voltage and load current in Figure-19 using an ideal diode.
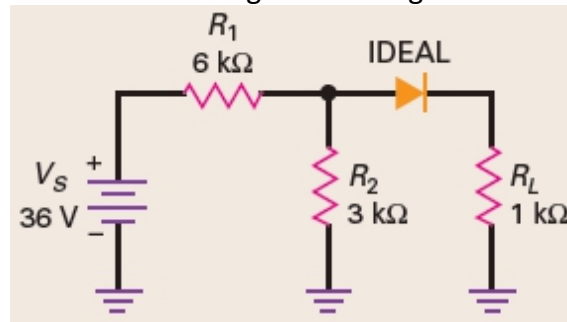
Figure-19

SOLUTION

One way to solve this problem is to Thevenize the circuit to the left of the diode. Looking from the diode back toward the source, we see a voltage divider with 6 kΩ and 3 kΩ. The Thevenin voltage is 12 V, and the Thevenin resistance is 2 kΩ. Figure-20 shows the Thevenin circuit driving the diode.
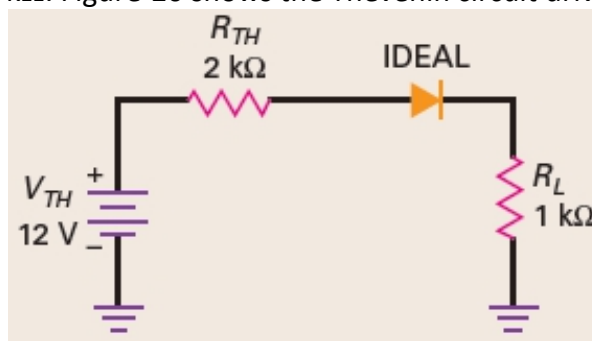
Figure-20

Now that we have a series circuit, we can see that the diode is forward biased. Visualize the diode as a closed switch. Then, the remaining calculations are:

$$I_L = 12V/3k\Omega = 4\ mA\ and$$
$$V_L = (4\ mA)\ (1\ kV) = 4\ V$$

You don't have to use Thevenin's theorem. You can analyze Figure-19 by visualizing the diode as a closed switch. Then, you have 3 kΩ in parallel with 1 kΩ, equivalent to 750 Ω. Using Ohm's law, you can calculate a voltage drop of 32 V across the 6 kΩ. The rest of the analysis produces the same load voltage and load current.

PRACTICE PROBLEM 3

Using Figure-19, change the 36 V source to 18 V and solve for the load voltage and load current using an ideal diode.

1.5   The Second Approximation

- The ideal approximation is all right in most troubleshooting situations. But we are not always troubleshooting. Sometimes, we want a more accurate value for load current and load voltage. This is where the second approximation comes in.

- Figure-21 shows the graph of current versus voltage for the second approximation. The graph says that no current exists until 0.7 V appears across the diode. At this point, the diode turns on. Thereafter, only 0.7 V can appear across the diode, no matter what the current.
- Figure-22 shows the equivalent circuit for the second approximation of a silicon diode. We think of the diode as a switch in series with a barrier potential of 0.7 V. If the Thevenin voltage facing the diode is greater than 0.7 V, the switch will close. When conducting, then the diode voltage is 0.7 V for any forward current.
- On the other hand, if the Thevenin voltage is less than 0.7 V, the switch will open. In this case, there is no current through the diode.
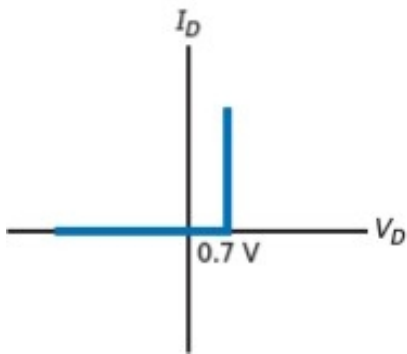
Figure- 21 Diode curve for second approximation
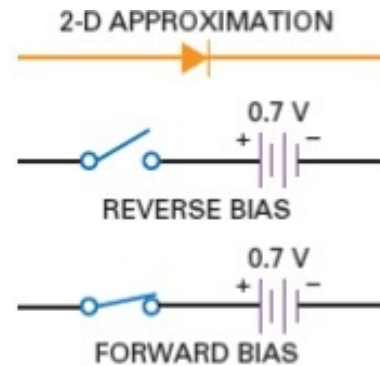
Figure-22 Equivalent circuit for second approximation

Example 4

Use the second approximation to calculate the load voltage, load current, and diode power in Figure-23.
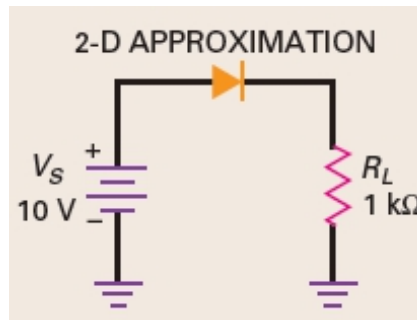
Figure-23

SOLUTION

Since the diode is forward biased, it is equivalent to a battery of 0.7 V. This means that the load voltage equals the source voltage minus the diode drop:

$$V_L = 10\ V - 0.7\ V = 9.3\ V$$

With Ohm's law, the load current is:

$$IL = 9.3V/1k\Omega = 9.3\ mA$$

The diode power is

$$PD = (0.7\ V)\ (9.3\ mA) = 6.51\ mW$$

PRACTICE PROBLEM 4

Using Figure-23, change the source voltage to 5 V and calculate the new load voltage, current, and diode power.

1.6 The Third Approximation

- In the third approximation of a diode, we include the bulk resistance R_B. Figure-24 shows the effect that R_B has on the diode curve.
- After the silicon diode turns on, the voltage increases linearly with an increase in current. The greater the current, the larger the diode voltage because of the voltage drop across the bulk resistance.
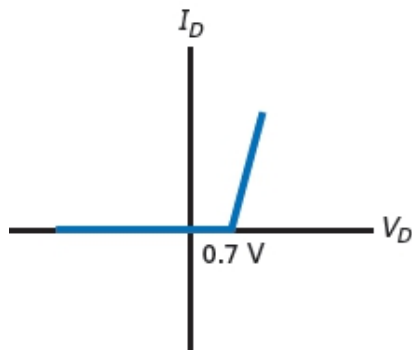
Figure-24 Diode curve for third approximation
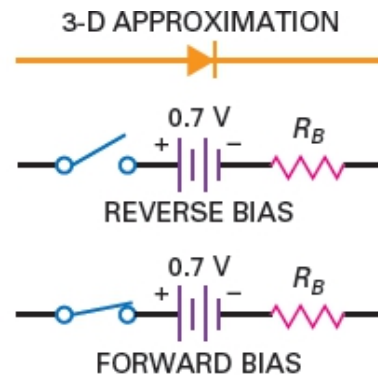
Figure-25 Equivalent circuit for third approximation

- The equivalent circuit for the third approximation is a switch in series with a barrier potential of 0.7 V and a resistance of RB (see Figure-25). When the diode voltage is larger than 0.7 V, the diode conducts. During conduction, the total voltage across the diode is:

$$V_D = 0.7\ V + I_D R_B \text{-----------------------------------}(5)$$

- Often, the bulk resistance is less than 1Ω, and we can safely ignore it in our calculations. A useful guideline for ignoring bulk resistance is this definition:

$$\textit{Ignore bulk:} \quad < \quad . \quad \text{------------------------------}(6)$$

- This says to ignore the bulk resistance when it is less than 1/100 of the Thevenin resistance facing the diode. When this condition is satisfied, the error is less than 1 percent. The third approximation is rarely used by technicians because circuit designers usually satisfy Eq. (6).

Example 5

The 1N4001 of Figure-26 has a bulk resistance of 0.23 Ω. What is the load voltage, load current, and diode power?
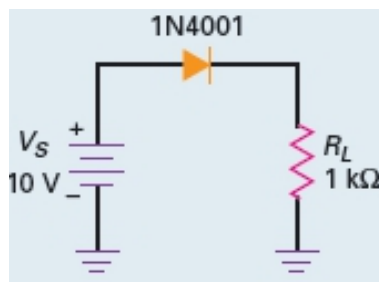
Figure-26
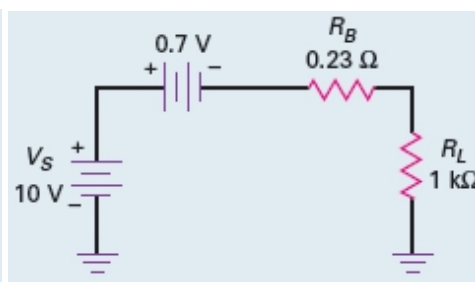
Figure-27
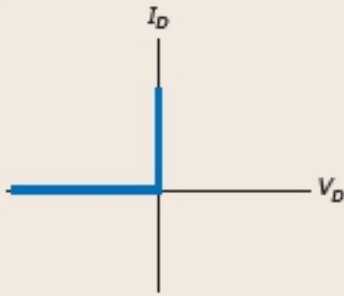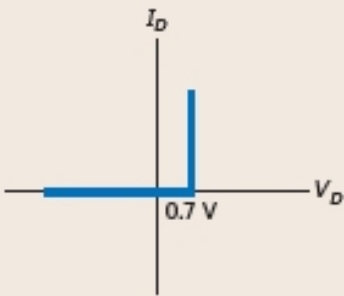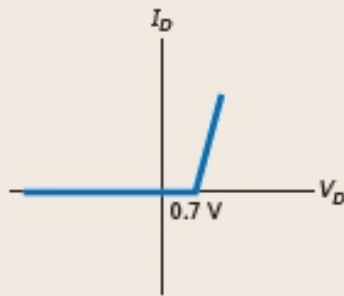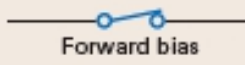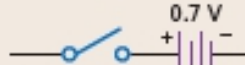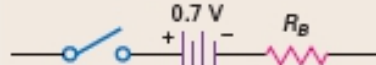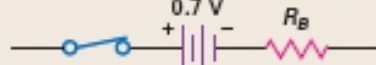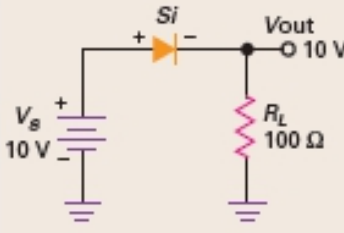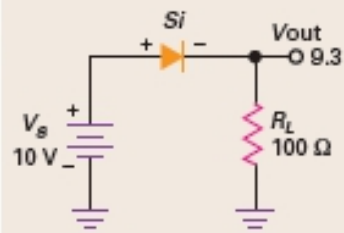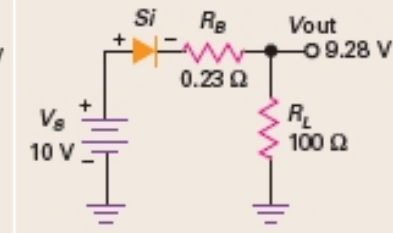
SOLUTION

Replacing the diode with its third approximation, we get Figure-27. The bulk resistance is **small enough to ignore because it is less than 1/100 of the load resistance**. In this case, we can use the second

approximation to solve the problem then we found a load voltage, load current, and diode power of 9.3 V, 9.3 mA, and 6.51 mW.

Summary of Diode Approximations

	First or ideal	Second or practical	Third
When used	Troubleshooting or quick analysis	Analysis at technician level	High-level or engineering-level analysis
Diode curve			
Equivalent circuit			
Circuit example			

1.7   Testing of Diode with Multimeter (Troubleshooting)

- You can quickly check the condition of a diode with an ohmmeter on a medium to high resistance range. Measure the dc resistance of the diode in either direction, and then reverse the leads and measure the dc resistance again.
- The forward current will depend on which ohmmeter range is used, which means that you get different readings on different ranges.
- The main thing to look for, however, is a high ratio of reverse to forward resistance. For typical silicon diodes used in electronics work, the ratio should be higher than **1000:1**. Remember to use a high enough resistance range to avoid the possibility of diode damage.
- Normally, the R × 100 or R × 1K ranges will provide proper safe measurements.

- Using an ohmmeter to check diodes is an example of go/no-go testing. You're really not interested in the exact dc resistance of the diode; all you want to know is whether the diode has a low resistance in the forward direction and a high resistance in the reverse direction.
- Diode troubles are indicated for any of the following: extremely low resistance in both directions (diode shorted); high resistance in both directions (diode open); somewhat low resistance in the reverse direction (called a leaky diode).
- When set to the ohms or resistance function, most digital multimeters (DMMs) do not have the required voltage and current output capability to properly test pn-junction diodes. Most DMMs do, however, have a special diode test range.
- When the meter is set to this range, it supplies a constant current of approximately 1 mA to whatever device is connected to its leads. When forward biased, the DMM will display the pn junction's forward voltage V_F shown in Figure-28. This forward voltage will generally be between **0.5 V** and **0.7 V** for normal silicon pn-junction diodes.
- When the diode is reverse biased by the test leads, the meter will give an over-range indication such as "**OL**" or "**1**" on the display as shown in Figure-29. A **shorted diode** would display a voltage of less than **0.5 V** in both directions.
- An open diode would be indicated by an **over-range** display in both directions. A leaky diode would display a voltage less than **2.0 V** in both directions.
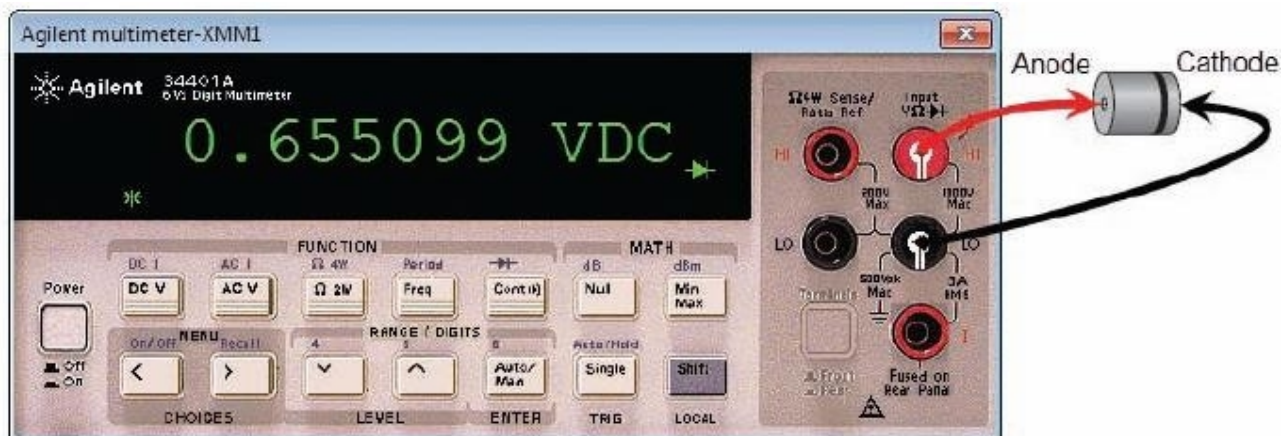
Figure-28
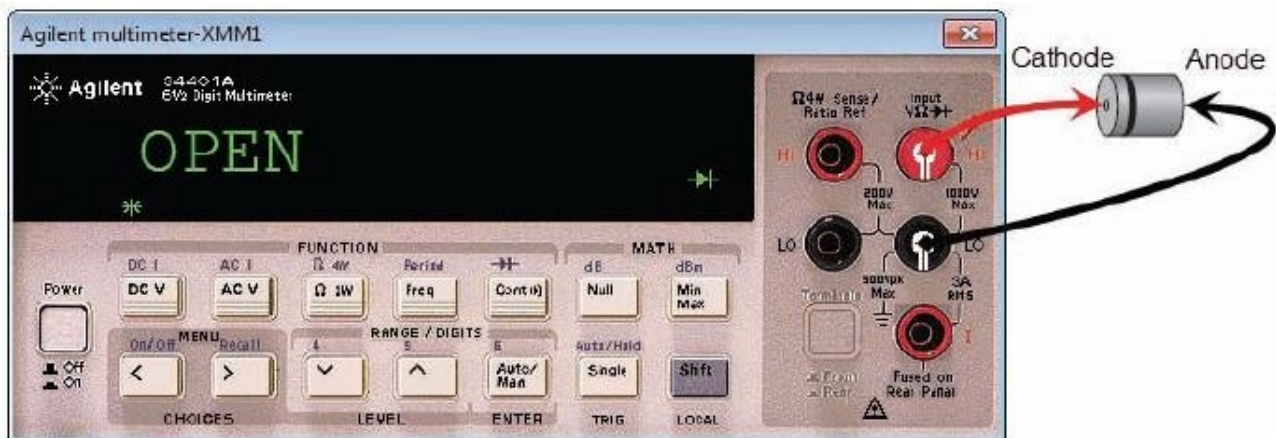
Figure-29

1.8   Surface-Mount Diodes

- Surface-mount **(SM)** diodes can be found anywhere there is a need for diode applications. **SM** diodes are small, efficient, and relatively easy to test, remove, and replace on the circuit board.
- Although there are a number of **SM** package styles, two basic styles dominate the industry: **SM** (surface mount) and **SOT** (small outline transistor).
- The **SM** package has two **L-bend** leads and a colored band on one end of the body to indicate the cathode lead. Figure-30 shows a typical set of dimensions.
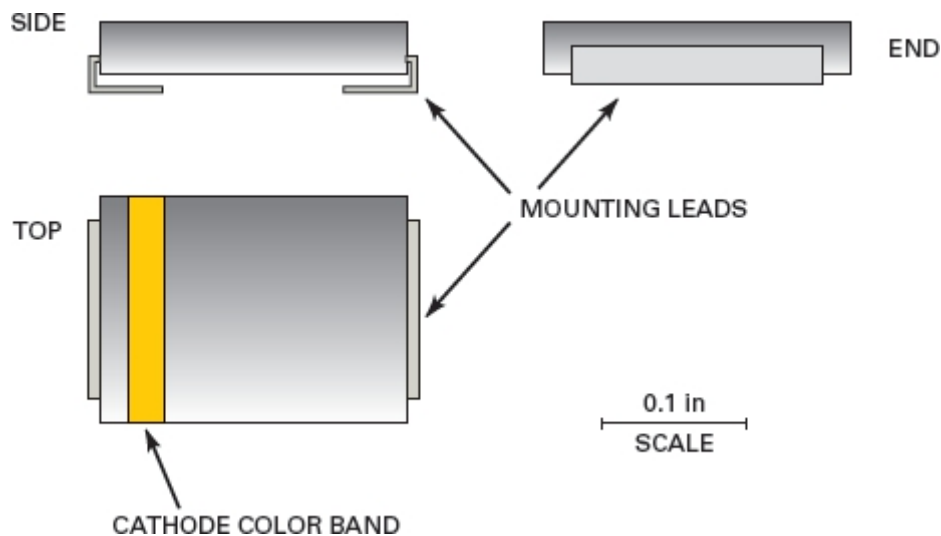
Figure-30 The two-terminal SM-style package used for SM diodes

- The length and width of the **SM** package are related to the current rating of the device. The larger the surface area, the higher the current rating. So an **SM** diode rated at **1 A** might have a surface area given by **0.181** by **0.115 in**. The **3 A** version, on the other hand, might measure **0.260** by **0.236 in**. The thickness tends to remain at about **0.103 in** for all current ratings.
- Increasing the surface area of an **SM**-style diode increases its ability to dissipate heat. Also, the corresponding increase in the width of the mounting terminals increases the thermal conductance to a virtual heat sink made up of the solder joints, mounting lands, and the circuit board itself.
- **SOT-23** packages have three gull-wing terminals (see Figure-31).
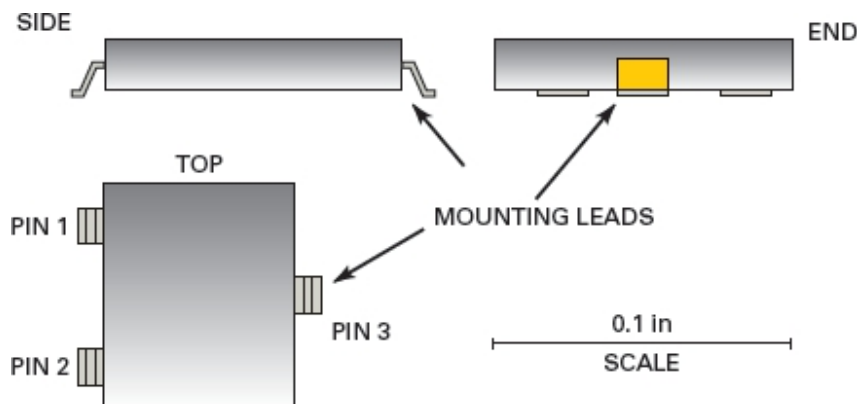
Figure-31 The SOT-23 is a three-terminal transistor package commonly used for SM diodes

- The terminals are numbered counter-clockwise from the top, pin 3 being alone on one side. However, there are no standard markings indicating which two terminals are used for the cathode and the anode.
- To determine the internal connections of the diode, you can look for clues printed on the circuit board, check the schematic diagram, or consult the diode manufacturer's data book.
- Some **SOT-style** packages include two diodes, which have a common-anode or common-cathode connection at one of the terminals.
- Diodes in **SOT-23** packages are small, no dimension being greater than **0.1 in**. Their small size makes it difficult to dissipate larger amounts of heat, so the diodes are generally rated at less than **1 A**.
- The small size also makes it impractical to label them with identification codes. As with many of the tiny **SM** devices, you have to determine the pin configuration from other clues on the circuit board and schematic diagram.

1.9 Why to study Diode Circuits?

- Most electronic systems, like HDTVs, audio power amplifiers, and computers, need a dc voltage to work properly. Since the power-line voltage is alternating and normally too high of a value, we need to reduce the ac line voltage and then convert it to a relatively constant dc output voltage.
- The section of the electronic system that produces this dc voltage is called the power supply.
- Within the power supply are circuits that allow current to flow in only one direction. These circuits are called rectifiers. Other circuits will filter and regulate the dc output.
- This section discusses rectifier circuits, filters, and an introduction to voltage regulators, clippers, clampers, and voltage multipliers.

1.10 The Half-Wave Rectifier

- Figure-31 shows a half-wave rectifier circuit. The ac source produces a sinusoidal voltage. Assuming an ideal diode, the positive half-cycle of source voltage will forward-bias the diode. Since the switch is closed, as shown in Figure-32, the positive half-cycle of source voltage will appear across the load resistor.
- On the negative half-cycle, the diode is reverse biased. In this case, the ideal diode will appear as an open switch, as shown in Figure-33, and no voltage appears across the load resistor.
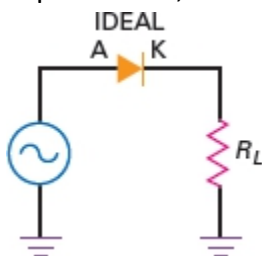
| Figure-31 Ideal half-wave rectifier | Figure-32 on positive half-cycle | Figure-33 on negative half-cycle |
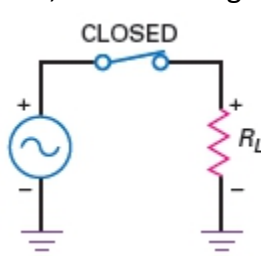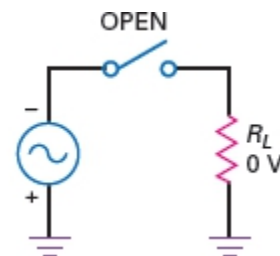
1.10.1 Ideal Waveforms

- Figure-34 shows a graphical representation of the input voltage waveform.

- It is a sine wave with an instantaneous value of *Vin* and a peak value of *Vp(in)*. A pure sinusoid like this has an average value of zero over one cycle because each instantaneous voltage has an equal and opposite voltage half a cycle later.
- If you measure this voltage with a dc voltmeter, you will get a reading of zero because a dc voltmeter indicates the average value.
- In the half-wave rectifier of Figure-31, the diode is conducting during the positive half-cycles but is non-conducting during the negative half-cycles. Because of this, the circuit **clips off the negative half-cycles**, as shown in Figure-35.
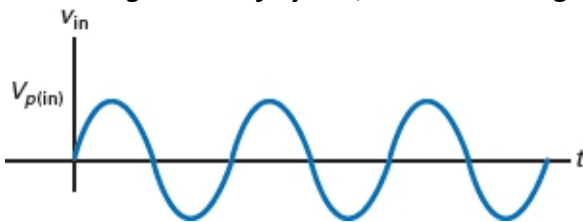
Figure-34 Input to half-wave rectifier

Figure-35 output of positive half-wave rectifier
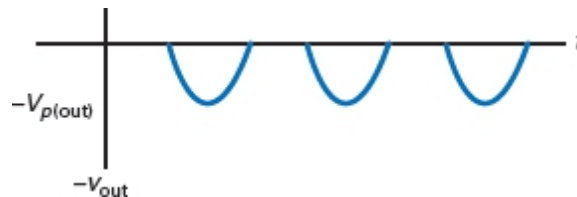
Figure-36 output of negative half-wave rectifier

- We call a waveform like this a half-wave signal. This half-wave voltage produces a unidirectional load current. This means that it flows in only one direction.
- If the diode were reversed, it would become forward biased when the input voltage was negative. As a result, the output pulses would be negative. This is shown in Figure-36.
- Notice how the negative peaks are offset from the positive peaks and follow the negative alternations of the input voltage.
- A half-wave signal like the one in Figure-35 is a pulsating dc voltage that increases to a maximum, decreases to zero, and then remains at zero during the negative half-cycle.
- This is not the kind of dc voltage we need for electronics equipment. What we need is a constant voltage, the same as you get from a battery.
- To get this kind of voltage, we need to filter the half-wave signal (discussed later in this chapter).
- When you are troubleshooting, you can use the ideal diode to analyze a half-wave rectifier. It's useful to remember that the peak output voltage equals the peak input voltage:

$$\textit{Ideal half wave:} \quad (\quad) = (\quad) \text{-----------------------}(7)$$

1.10.2 DC Value of Half-Wave Signal

- The dc value of a signal is the same as the average value. If you measure a signal with a dc voltmeter, the reading will equal the average value. In basic courses, the dc value of a half-wave signal is derived. The formula is:

$$\textit{Half wave:} \quad = \text{------------------------------} (8)$$

- The proof of this derivation requires calculus because we have to work out the average value over one cycle.
- Since $1/\pi \approx 0.318$, you may see Eq. (8) written as:

$$\approx .$$

- When the equation is written in this form, you can see that the dc or average value equals 31.8 percent of the peak value. For instance, if the peak voltage of the half-wave signal is 100 V, the dc voltage or average value is 31.8 V.

1.10.3 Output Frequency

- The output frequency is the same as the input frequency. This makes sense when you compare Figure-35 with Figure-34. Each cycle of input voltage produces one cycle of output voltage. Therefore, we can write:

$$\textbf{\textit{Half wave:}} \quad = \quad \text{-------------------------------------}\textbf{\textit{(9)}}$$

- We will use this derivation later with filters.

1.10.4 Second Approximation

- We don't get a perfect half-wave voltage across the load resistor. Because of the barrier potential, the diode does not turn on until the ac source voltage reaches approximately 0.7 V.
- When the peak source voltage is much greater than 0.7 V, the load voltage will resemble a half-wave signal. For instance, if the peak source voltage is 100 V, the load voltage will be close to a perfect half-wave voltage.
- If the peak source voltage is only 5 V, the load voltage will have a peak of only 4.3 V.
- When you need to get a better answer, use this derivation:

$$\textbf{\textit{2d half wave:}} \quad (\quad) = \quad (\quad) - \quad . \quad \text{------------------------}\textbf{\textit{(10)}}$$

1.10.5 Higher Approximations

- Most designers will make sure that the bulk resistance is much smaller than the Thevenin resistance facing the diode. Because of this, we can ignore bulk resistance in almost every case.
- If you must have better accuracy than you can get with the second approximation, you should use a computer and a circuit simulator like Multisim.

Example 6

Figure-37 shows a half-wave rectifier that you can build on the lab bench or on a computer screen with Multisim. An oscilloscope is across the 1 kΩ. Set the oscilloscope's vertical input coupling switch or setting to dc. This will show us the half-wave load voltage. Also, a multimeter is across the 1 kΩ to read the dc load voltage. Calculate the theoretical values of peak load voltage and the dc load voltage. Then, compare these values to the readings on the oscilloscope and the multimeter.
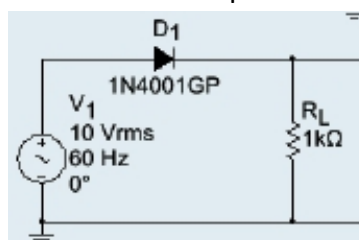
Figure-37

SOLUTION

- Figure-37 shows an ac source of 10 V and 60 Hz. Schematic diagrams usually show ac source voltages as effective or rms values. Recall that the effective value is the value of a dc voltage that produces the same heating effect as the ac voltage.
- Since the source voltage is **10 Vrms**, the first thing to do is calculate the peak value of the ac source. You know from earlier courses that the rms value of a sine wave equals:

$$= .$$

- Therefore, the peak source voltage in Figure-37 is:

$$= \frac{}{.} = \frac{}{.} = .$$

- With an ideal diode, the peak load voltage is:

$$Vp\ (out) = Vp(in) = 14.1\ V$$

- The dc load voltage is:

$$= \frac{}{} = \frac{.}{} = .$$

- With the second approximation, we get a peak load voltage of:

$$(\quad) = (\quad) - . \quad = . \quad - . \quad = .$$

And a dc load voltage of:

$$= \frac{}{} = \frac{.}{} = .$$

PRACTICE PROBLEM 5

Using Figure-37, change the ac source voltage to **15 V**. Calculate the second approximation dc load voltage Vdc.

1.11 The Transformer

- Power companies in the United States supply a nominal line voltage of **120 Vrms** and a frequency of 60 Hz. The actual voltage coming out of a power outlet may vary from **105** to **125 Vrms**, depending on the time of day, the locality, and other factors.
- Line voltage is too high for most of the circuits used in electronics equipment. This is why a transformer is commonly used in the power-supply section of almost all electronics equipment.
- The transformer steps the line voltage down to safer and lower levels that are more suitable for use with diodes, transistors, and other semiconductor devices.

1.11.1 Basic Idea

- Figure-38 shows a transformer. Here, you see line voltage applied to the primary winding of a transformer. Usually, the power plug has a third prong to ground the equipment. Because of the turn's ratio N_1/N_2, the secondary voltage is stepped down when N_1 is greater than N_2.

1.11.2 Phasing Dots

- Recall the meaning of the phasing dots shown at the upper ends of the windings. Dotted ends have the same instantaneous phase.
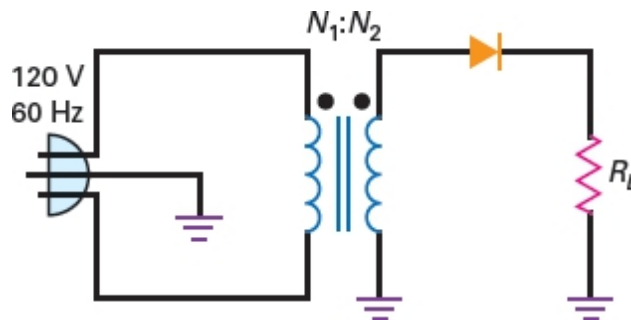
Figure-38 Half-wave rectifier with transformer

- In other words, when a positive half-cycle appears across the primary, a positive half-cycle appears across the secondary. If the secondary dot were on the ground end, the secondary voltage would be **180°** out of phase with the primary voltage.
- On the positive half-cycle of primary voltage, the secondary winding has a positive half sine wave across it and the diode is forward biased.
- On the negative half-cycle of primary voltage, the secondary winding has a negative half-cycle and the diode is reverse biased. Assuming an ideal diode, we will get a half-wave load voltage.

1.11.3 Turns Ratio

- Recall from your earlier course work the following derivation:

$$ = \quad — \quad \text{-------------------------------------- (11)}$$

- This says that the secondary voltage equals the primary voltage divided by the turn's ratio.
- In other words the secondary voltage equals the inverse turns ratio times the primary voltage.
- You can use either formula for rms, peak values, and instantaneous voltages.
- Most of the time, we will use Eq. (11) with rms values because ac source voltages are almost always specified as rms values.
- The terms step up and step down are also encountered when dealing with transformers. These terms always relate the secondary voltage to the primary voltage.
- This means that a step-up transformer will produce a secondary voltage that is larger than the primary, and a step-down transformer will produce a secondary voltage that is smaller than the primary.

Example 7

What are the peak load voltage and dc load voltage in Figure-39?
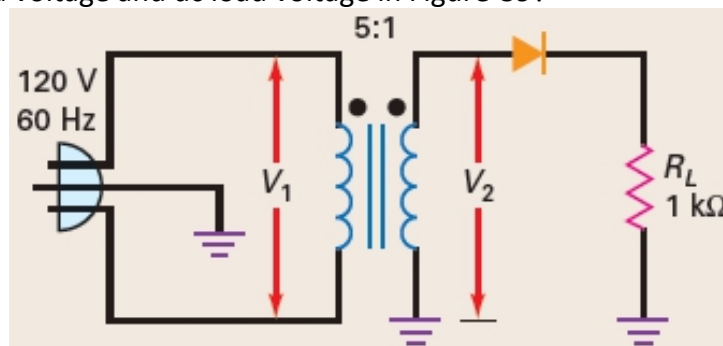
Figure-39

SOLUTION

The transformer has a turn's ratio of 5:1. This means that the rms secondary voltage is one-fifth of the primary voltage:

$$= \underline{\quad\quad} =$$

And the peak secondary voltage is:

$$= \underline{\quad\quad} =$$

With an ideal diode, the peak load voltage is:

$$(\quad) =$$

The dc load voltage is:

$$= \underline{\quad} = \underline{\quad\quad} = .$$

With the second approximation, the peak load voltage is:

$$(\quad) = \quad - . \quad = .$$

And the dc load voltage is:

$$= \underline{\quad} = \underline{\quad\quad} = .$$

PRACTICE PROBLEM 6

Using Figure-39, change the transformer's turns ratio to *2:1* and solve for the ideal dc load voltage.

1.12 The Full-Wave Rectifier

- Figure-40 shows a full-wave rectifier circuit. Notice the grounded center tap on the secondary winding. The full-wave rectifier is equivalent to two half-wave rectifiers. Because of the center tap, each of these rectifiers has an input voltage equal to half the secondary voltage.
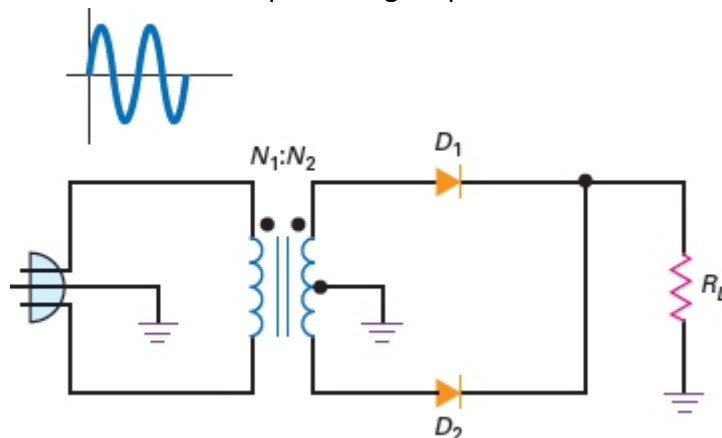
Figure-40 Full-wave rectifier

- Diode D1 conducts on the positive half-cycle, and diode D2 conducts on the negative half-cycle. As a result, the rectified load current flows during both half-cycles.
- The full-wave rectifier acts the same as two back-to-back half-wave rectifiers.
- Figure-41 shows the equivalent circuit for the positive half-cycle. As you see, D1 is forward biased. This produces a positive load voltage as indicated by the plus-minus polarity across the load resistor.
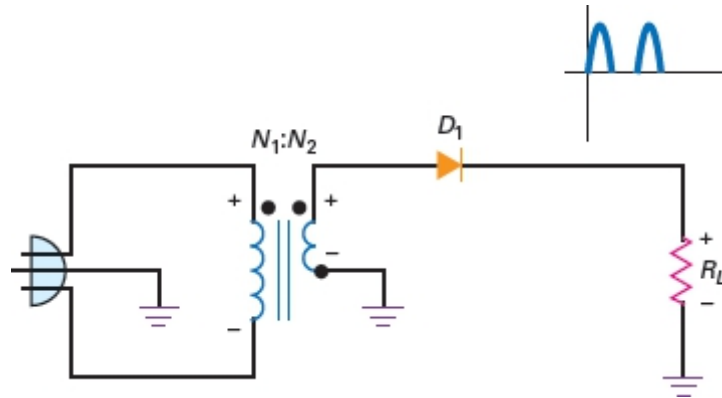
Figure-41 Equivalent circuit for positive half-cycle

- Figure-42 shows the equivalent circuit for the negative half-cycle. This time, D2 is forward biased. As you can see, this also produces a positive load voltage.
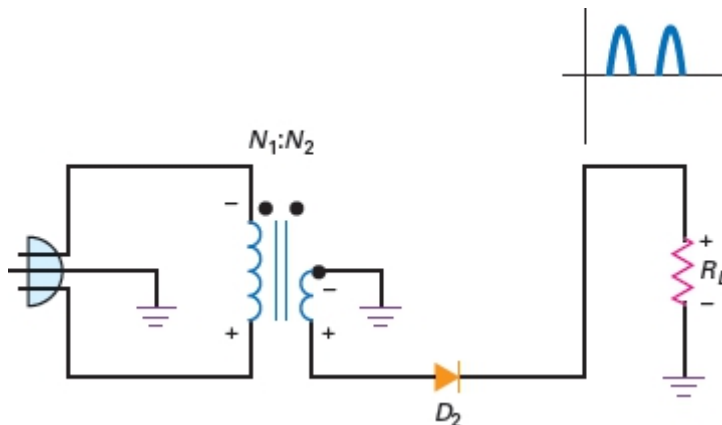
Figure-42 Equivalent circuit for negative half-cycle

- During both half-cycles, the load voltage has the same polarity and the load current is in the same direction. The circuit is called a full-wave rectifier because it has changed the ac input voltage to the pulsating dc output voltage shown in Figure-43. This waveform has some interesting properties that we will now discuss.
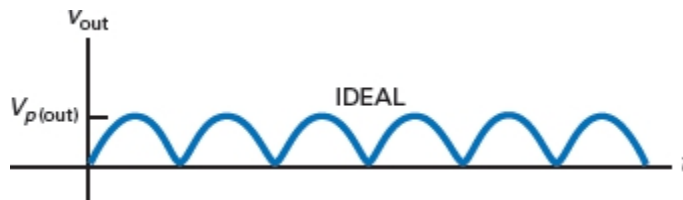
Figure-43 Full-wave output

1.12.1 DC or Average Value

- Since the full-wave signal has twice as many positive cycles as the half-wave signal, the dc or average value is twice as much, given by:

$$\textbf{\textit{Full wave:}} \qquad = \frac{\quad}{\quad} \qquad \textbf{\textit{(12)}}$$

- Since $2/\pi = 0.636$, you may see Eq. (12) written as:

$$\approx \quad$$

- In this form, you can see that the dc or average value equals **63.6** percent of the peak value. For instance, if the peak voltage of the full-wave signal is **100 V**, the dc voltage or average value is **63.6 V**.

1.12.2 Output Frequency

- With a half-wave rectifier, the output frequency equals the input frequency. But with a full-wave rectifier, something unusual happens to the output frequency.
- The ac line voltage has a frequency of 60 Hz. Therefore, the input period equals:

$$= \_ = \frac{\quad}{\quad} = \quad .$$

- Because of the full-wave rectification, the period of the full-wave signal is half the input period:

$$= \quad . \; (\quad . \quad) = \quad .$$

(If there is any doubt in your mind, compare Figure-43 to Figure-35.) When we calculate the output frequency, we get:

$$= \frac{\quad}{\quad} = \frac{\quad}{\quad .} =$$

- The frequency of the full-wave signal is double the input frequency. This makes sense. A full-wave output has twice as many cycles as the sine-wave input has.
- The full-wave rectifier inverts each negative half-cycle so that we get double the number of positive half-cycles. The effect is to double the frequency. As a derivation:

$$: \quad = \quad \text{---------------------------------} \textbf{(13)}$$

1.12.3 Second Approximation

- Since the full-wave rectifier is like two back-to-back half-wave rectifiers, we can use the second approximation given earlier. The idea is to subtract **0.7 V** from the ideal peak output voltage.

Example 8

Figure-44 shows a full-wave rectifier that you can build on a lab bench or on a computer screen with Multisim. Calculate the peak input and output voltages.
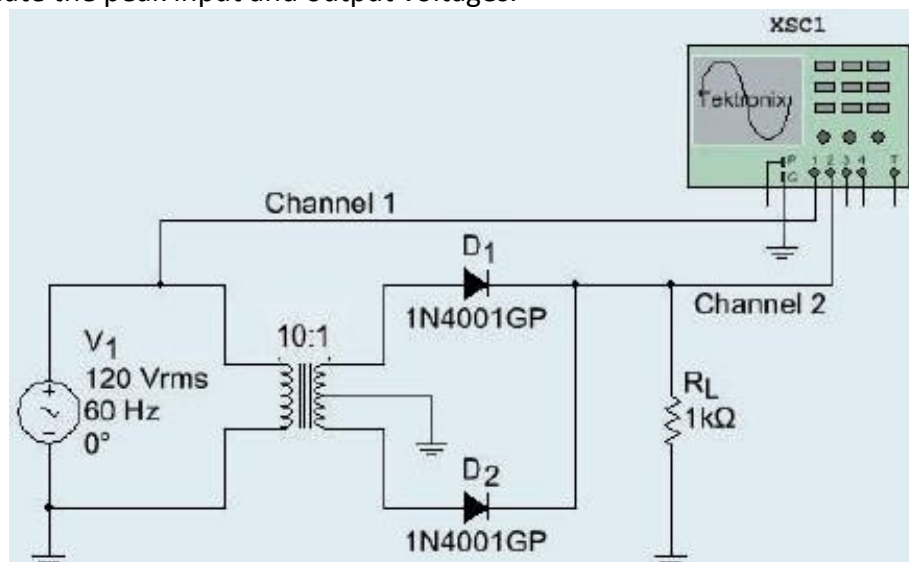
Figure-44

SOLUTION

The peak primary voltage is:

$$( ) = \dfrac{\quad}{.} = \dfrac{\quad}{.} =$$

Because of the 10:1 step-down transformer, the peak secondary voltage is:

$$( ) = ( ) \dfrac{\quad}{} = \dfrac{\quad}{} =$$

The full-wave rectifier acts like two back-to-back half-wave rectifiers. Because of the center tap, the input voltage to each half-wave rectifier is only half the secondary voltage:

$$( ) = . \quad ( ) = .$$

Ideally, the output voltage is:

$$( ) = .$$

Using the second approximation:

$$( ) = . \quad - . \quad = .$$

1.13   The Bridge Rectifier

- Figure-45 shows a bridge rectifier circuit. The bridge rectifier is similar to a full-wave rectifier because it produces a full-wave output voltage.
- Diodes D1 and D2 conduct on the positive half-cycle, and D3 and D4 conduct on the negative half-cycle. As a result, the rectified load current flows during both half-cycles.
- Figure-46 shows the equivalent circuit for the positive half-cycle. As you can see, D1 and D2 are forward biased. This produces a positive load voltage as indicated by the plus-minus polarity across the load resistor.
- As a memory aid, visualize D2 shorted. Then, the circuit that remains is a half-wave rectifier, which we are already familiar with.
- Figure-47 shows the equivalent circuit for the negative half-cycle. This time, D3 and D4 are forward biased. This also produces a positive load voltage.
- If you visualize D3 shorted, the circuit looks like a half-wave rectifier. So the bridge rectifier acts like two back-to-back half-wave rectifiers.
- During both half-cycles, the load voltage has the same polarity and the load current is in the same direction. The circuit has changed the ac input voltage to the pulsating dc output voltage shown in Figure-48. Note the advantage of this type of full-wave rectification over the center-tapped version in the previous section: *The entire secondary voltage can be used*.
- Figure-49 shows bridge rectifier packages that contain all four diodes.
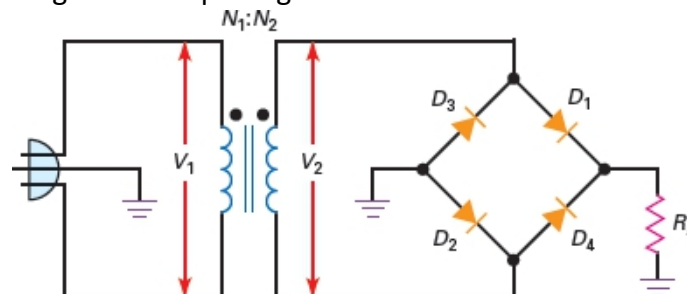
Figure-45 Bridge rectifier
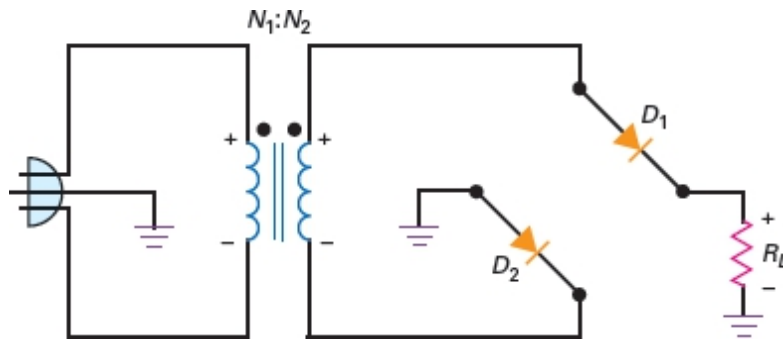
Figure-46 Equivalent circuit for positive half-cycle
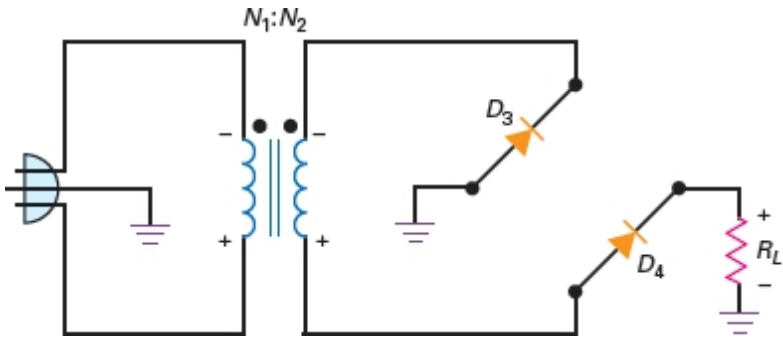
Figure-47 Equivalent circuit for negative half-cycle
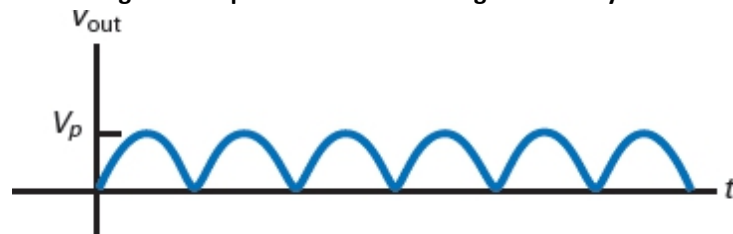
Figure-48 Full-wave output

Figure-49 bridge rectifier packages

1.13.1 Average Value and Output Frequency

- Because a bridge rectifier produces a full-wave output, the equations for average value and output frequency are the same as those given for a full-wave rectifier:

$$\textit{Full wave:} \quad = \frac{}{}$$

And

$$: \quad =$$

- The average value is 63.6 percent of the peak value, and the output frequency is 120 Hz, given a line frequency of 60 Hz.
- One advantage of a bridge rectifier is that all the secondary voltage is used as the input to the rectifier.
- Given the same transformer, we get twice as much peak voltage and twice as much dc voltage with a bridge rectifier as with a full-wave rectifier.
- Doubling the dc output voltage compensates for having to use two extra diodes. As a rule, you will see the bridge rectifier used a lot more than the full-wave rectifier.
- Incidentally, the full-wave rectifier was in use for many years before the bridge rectifier was used. For this reason, it has retained the name full-wave rectifier even though a bridge rectifier also has a full-wave output.
- To distinguish the full-wave rectifier from the bridge rectifier, some literature may refer to a full-wave rectifier as a conventional full-wave rectifier, a two-diode full-wave rectifier, or a center-tapped full-wave rectifier.

1.13.2 Second Approximation and Other Losses

- Since the bridge rectifier has two diodes in the conducting path, the peak output voltage is given by:

$$: \quad (\quad) = \quad (\quad) - \quad . \quad \text{--------------------------- (14)}$$

- As you can see, we have to subtract two diode drops from the peak to get a more accurate value of peak load voltage. Summary Table compares the three rectifiers and their properties.

	Half-wave	Full-wave	Bridge
Number of diodes	1	2	4
Rectifier input	$V_{p(2)}$	$0.5V_{p(2)}$	$V_{p(2)}$
Peak output (ideal)	$V_{p(2)}$	$0.5V_{p(2)}$	$V_{p(2)}$
Peak output (2d)	$V_{p(2)} - 0.7\text{ V}$	$0.5V_{p(2)} - 0.7\text{ V}$	$V_{p(2)} - 1.4\text{ V}$
DC output	$V_{p(out)}/\pi$	$2V_{p(out)}/\pi$	$2V_{p(out)}/\pi$
Ripple frequency	f_{in}	$2f_{in}$	$2f_{in}$

*Vp(2) = peak secondary voltage; Vp(out) = peak output voltage.

1.14 The Choke-Input Filter

- At one time, the choke-input filter was widely used to filter the output of a rectifier. Although not used much anymore because of its cost, bulk, and weight, this type of filter has instructional value and helps make it easier to understand other filters.

1.14.1 Basic Idea

- Look at Figure-50. This type of filter is called a choke-input filter. The ac source produces a current in the inductor, capacitor, and resistor. The ac current in each component depends on the inductive reactance, capacitive reactance, and the resistance. The inductor has a reactance given by:

$$=$$

- The capacitor has a reactance given by:

$$= \underline{\quad}$$

- As you learned in previous courses, the choke (or inductor) has the **primary characteristic of opposing a change in current**. Because of this, a choke-input filter ideally reduces the ac current in the load resistor to zero.
- To a second approximation, it reduces the ac load current to a very small value. Let us find out why?
- The first requirement of a well-designed choke-input filter is to have X_C at the input frequency be much smaller than R_L. When this condition is satisfied, we can ignore the load resistance and use the equivalent circuit of Figure-51.
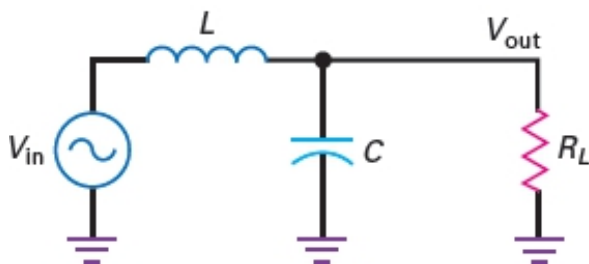
Figure-50 Choke-input filter   **Figure-51 AC-equivalent circuit**
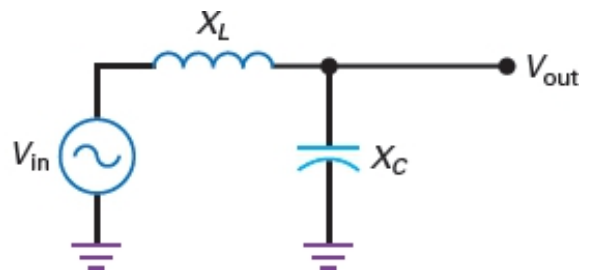
- The second requirement of a well-designed choke-input filter is to have X_L be much greater than X_C at the input frequency. When this condition is satisfied, the ac output voltage approaches zero.
- On the other hand, since the choke approximates a **short circuit** at **0 Hz** and the capacitor **approximates an open** at **0 Hz**, the dc current can be passed to the load resistance with minimum loss.
- In Figure-51, the circuit acts like a reactive voltage divider. When X_L is much greater than X_C, almost all the ac voltage is dropped across the choke. In this case, the ac output voltage equals:

$$\approx \underline{\quad} \quad \text{-------------------------------- (15)}$$

- For instance, if $X_L = 10\ k\Omega$, $X_C = 100\ \Omega$, and $V_{in} = 15\ V$, the ac output voltage is:

$$\approx \frac{\Omega}{\Omega} = \ .$$

- In this example, the choke-input filter reduces the ac voltage by a factor of 100.

1.14.2 Filtering the Output of a Rectifier

- Figure-52 shows a choke-input filter between a rectifier and a load. The rectifier can be a half-wave, full-wave, or bridge type. What effect does the choke input filter have on the load voltage?
- The easiest way to solve this problem is to use the superposition theorem. Recall what this theorem says: *If you have two or more sources, you can analyze the circuit for each source separately and then add the individual voltages to get the total voltage.*
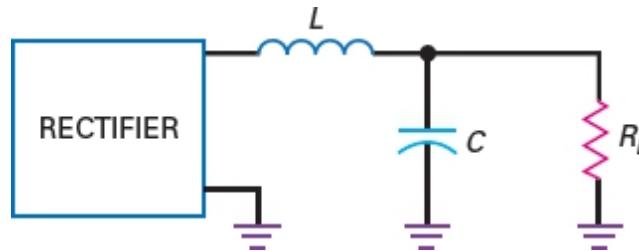
Figure-52 Rectifier with Choke-input filter

- The rectifier output has two different components: a dc voltage (the average value) and an ac voltage (the fluctuating part), as shown in Figure-53.
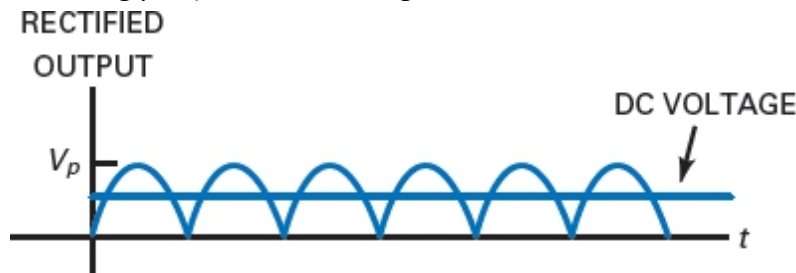
Figure-53 Rectifier output has dc and ac components

- Each of these voltages acts like a separate source. As far as the ac voltage is concerned, X_L is much greater than X_C, and this results in very little ac voltage across the load resistor. Even though the ac component is not a pure sine wave, Eq. (15) is still a close approximation for the ac load voltage.
- The circuit acts like Figure-54 as far as dc voltage is concerned. At *0 Hz*, the inductive reactance is zero and the capacitive reactance is infinite. Only the series resistance of the inductor windings remains.
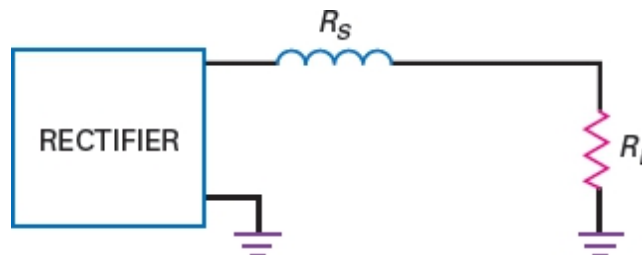
Figure-54 DC-equivalent circuit

- Making R_S much smaller than R_L causes most of the dc component to appear across the load resistor.

- That's how a choke-input filter works: Almost all of the dc component is passed on to the load resistor, and almost all of the ac component is blocked.
- In this way, we get an almost perfect dc voltage, one that is almost constant, like the voltage out of a battery. Figure-55 shows the filtered output for a full-wave signal.

FILTERED
OUTPUT

$0.636\ V_p$

t
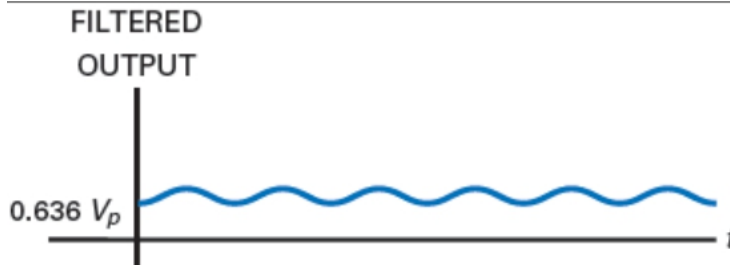
Figure-55 filter output is a dc voltage with small ripple

- The only deviation from a perfect dc voltage is the small ac load voltage shown in Figure-55. This small ac load voltage is called ripple. With an oscilloscope, we can measure its peak-to-peak value.
- To measure the ripple value, set the oscilloscope's vertical input coupling switch or setting to ac instead of dc. This will allow you to see the ac component of the waveform while blocking the dc or average value.

1.14.3 Main Disadvantage

- A *power supply* is the circuit inside electronics equipment that converts the ac input voltage to an almost perfect dc output voltage. It includes a rectifier and a filter.
- The trend nowadays is toward low-voltage, high-current power supplies. Because line frequency is only 60 Hz, large inductances have to be used to get enough reactance for adequate filtering. But large inductors have large winding resistances, which create a serious design problem with large load currents.
- In other words, too much dc voltage is dropped across the choke resistance. Furthermore, bulky inductors are not suitable for modern semiconductor circuits, where the emphasis is on lightweight designs.

1.14.4 Switching Regulators

- One important application does exist for the choke-input filter. A switching regulator is a special kind of power supply used in computers, monitors, and an increasing variety of equipment.
- The frequency used in a switching regulator is much higher than 60 Hz.
- Typically, the frequency being filtered is above 20 kHz. At this much higher frequency, we can use much smaller inductors to design efficient choke-input filters.

1.15 The Capacitor-Input Filter

- The choke-input filter produces a dc output voltage equal to the average value of the rectified voltage. The capacitor-input filter produces a dc output voltage equal to the peak value of the rectified voltage. This type of filter is the most widely used in power supplies.

1.15.1 Basic Idea

- Figure-56a shows an ac source, a diode, and a capacitor. The key to understanding a capacitor-input filter is understanding what this simple circuit does during the first quarter-cycle.
- Initially, the capacitor is uncharged. During the first quarter-cycle of Figure-56b, the diode is forward biased.
- Since it ideally acts like a closed switch, the capacitor charges, and its voltage equals the source voltage at each instant of the first quarter-cycle. The charging continues until the input reaches its maximum value. At this point, the capacitor voltage equals **Vp**.
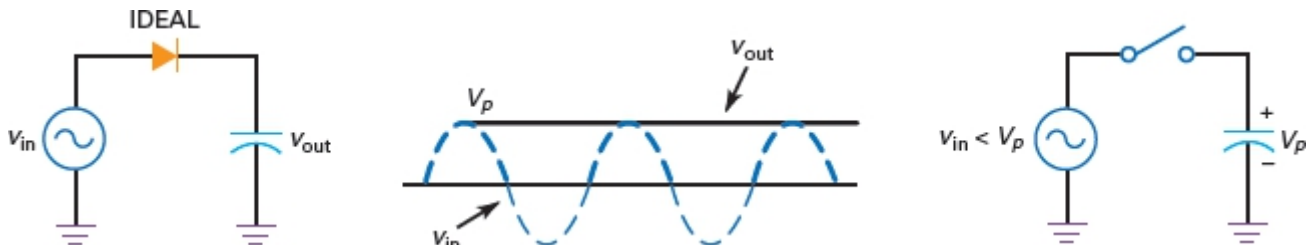
Figure-56 (a) Unloaded capacitor-input filter (b) output is pure dc voltage (c) capacitor remains charged when diode is off

- After the input voltage reaches the peak, it starts to decrease. As soon as the input voltage is less than **Vp**, the diode turns off. In this case, it acts like the open switch of Figure-56c. During the remaining cycles, the capacitor stays fully charged and the diode remains open.
- This is why the output voltage of Figure-56b is constant and equal to **Vp**. Ideally, all that the capacitor-input filter does is charge the capacitor to the peak voltage during the first quarter-cycle. This peak voltage is constant, the perfect dc voltage we need for electronics equipment.
- There's only one problem: There is no load resistor.

1.15.2 Effect of Load Resistor

- For the capacitor-input filter to be useful, we need to connect a load resistor across the capacitor, as shown in Figure-57a. As long as the **RLC** time constant is much greater than the period, the capacitor remains almost fully charged and the load voltage is approximately **Vp**.
- The only deviation from a perfect dc voltage is the small ripple seen in Figure-57b. The smaller the peak-to-peak value of this ripple, the more closely the output approaches a perfect dc voltage.
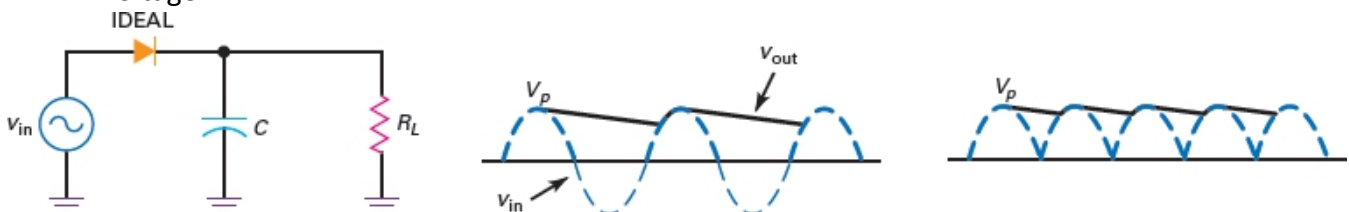
Figure-57 (a) Loaded capacitor-input filter (b) output is a dc voltage with small ripple (c) full-wave output has less ripple

- Between peaks, the diode is off and the capacitor discharges through the load resistor. In other words, the capacitor supplies the load current.
- Since the capacitor discharges only slightly between peaks, the peak-to-peak ripple is small.
- When the next peak arrives, the diode conducts briefly and recharges the capacitor to the peak value. A key question is: What size should the capacitor be for proper operation?

- Before discussing capacitor size, consider what happens with the other rectifier circuits.

1.15.3 Full-Wave Filtering

- If we connect a full-wave or bridge rectifier to a capacitor-input filter, the peak-to- peak ripple is cut in half. Figure-57c shows why.
- When a full-wave voltage is applied to the RC circuit, the capacitor discharges for only half as long. Therefore, the peak-to-peak ripple is half the size it would be with a half-wave rectifier.

1.15.4 The Ripple Formula

- Here is a derivation we will use to estimate the peak-to-peak ripple out of any capacitor-input filter:

$$= \text{—} \text{-------------------------------- (16)}$$

Where,   *V_R = peak-to-peak ripple voltage*
   I = dc load current
   f = ripple frequency
   C = capacitance

- This is an approximation, not an exact derivation. We can use this formula to estimate the peak-to-peak ripple. When a more accurate answer is needed, one solution is to use a computer with a circuit simulator like Multisim.
- For instance, if the dc load current is **10 mA** and the capacitance is **200 μF**, the ripple with a bridge rectifier and a capacitor-input filter is:

$$= \frac{\qquad}{(\qquad)(\qquad)} = \quad . \qquad -$$

- When using this derivation, remember two things. First, the ripple is in peak-to-peak (p-p) voltage. This is useful because you normally measure ripple voltage with an oscilloscope. Second, the formula works with half-wave or full-wave voltages. Use 60 Hz for half wave, and 120 Hz for full wave.
- You should use an oscilloscope for ripple measurements if one is available. If not, you can use an ac voltmeter, although there will be a significant error in the measurement.
- Most ac voltmeters are calibrated to read the rms value of a sine wave. Since the ripple is not a sine wave, you may get a measurement error of as much as 25 percent, depending on the design of the ac voltmeter.
- But this should be no problem when you are troubleshooting, since you will be looking for much larger changes in ripple.
- If you do use an ac voltmeter to measure the ripple, you can convert the peak-to-peak value given by Eq. (16) to an rms value using the following formula for a sine wave:

$$= \frac{-}{\sqrt{}}$$

- Dividing by 2 converts the peak-to-peak value to a peak value, and dividing by √2 gives the rms value of a sine wave with the same peak-to-peak value as the ripple voltage.

1.15.5 Exact DC Load Voltage

- It is difficult to calculate the exact dc load voltage in a bridge rectifier with a capacitor-input filter.
- To begin with, we have the two diode drops that are subtracted from the peak voltage. Besides the diode drops, an additional voltage drop occurs, as follows: The diodes conduct heavily when recharging the capacitor because they are on for only a short time during each cycle.
- This brief but large current has to flow through the transformer windings and the bulk resistance of the diodes. In our examples, we will calculate either the ideal output or the output with the second approximation of a diode, remembering that the actual dc voltage is slightly lower.

Example 9

What is the dc load voltage and ripple in Figure-58?
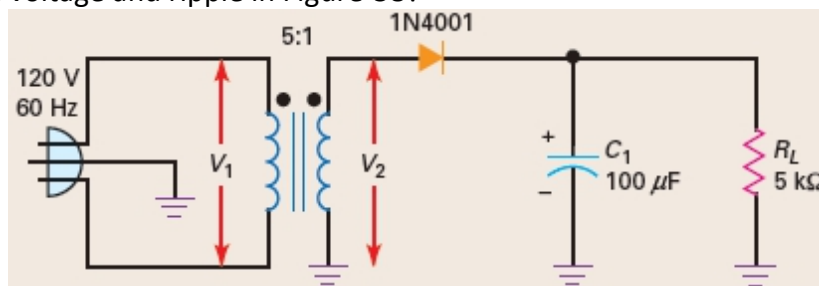
Figure-58

SOLUTION

The rms secondary voltage is:

$$= \underline{\quad} =$$

The peak secondary voltage is:

$$= \underline{\quad} =$$

Assuming an ideal diode and small ripple, the dc load voltage is:

$$=$$

To calculate the ripple, we first need to get the dc load current:

$$= \underline{\quad} = \frac{\quad}{\Omega} = \quad .$$

Now we can use Eq. (16) to get:

$$= \frac{\cdot}{(\quad)(\quad)} = \quad . \quad - \approx \quad . \quad -$$

- We rounded the ripple to two significant digits because it is an approximation and cannot be accurately measured with an oscilloscope with greater precision.
- Here is how to improve the answer slightly: There is about *0.7 V* across a silicon diode when it is conducting. Therefore, the peak voltage across the load will be closer to *33.3 V* than to *34 V*. The ripple also lowers the dc voltage slightly.
- So the actual dc load voltage will be closer to *33 V* than to *34 V*. But these are minor deviations. Ideal answers are usually adequate for troubleshooting and preliminary analysis.
- A final point about the circuit. The plus and minus signs on the filter capacitor indicates a polarized capacitor, one whose plus side must be connected to the positive rectifier output.

- In Figure-59, the plus sign on the capacitor case is correctly connected to the positive output voltage. You must look carefully at the capacitor case when you are building or troubleshooting a circuit to find out whether it is polarized or not.
- If you reverse the polarity of the rectifier diodes and build a negative power-supply circuit, be sure to connect the capacitor's negative side to the negative output voltage point and the positive capacitor side to circuit ground.
- Power supplies often use polarized electrolytic capacitors because this type can provide high values of capacitance in small packages. As discussed in earlier courses, electrolytic capacitors must be connected with the correct polarity to produce the oxide film. *If an electrolytic capacitor is connected in opposite polarity, it becomes hot and may explode.*
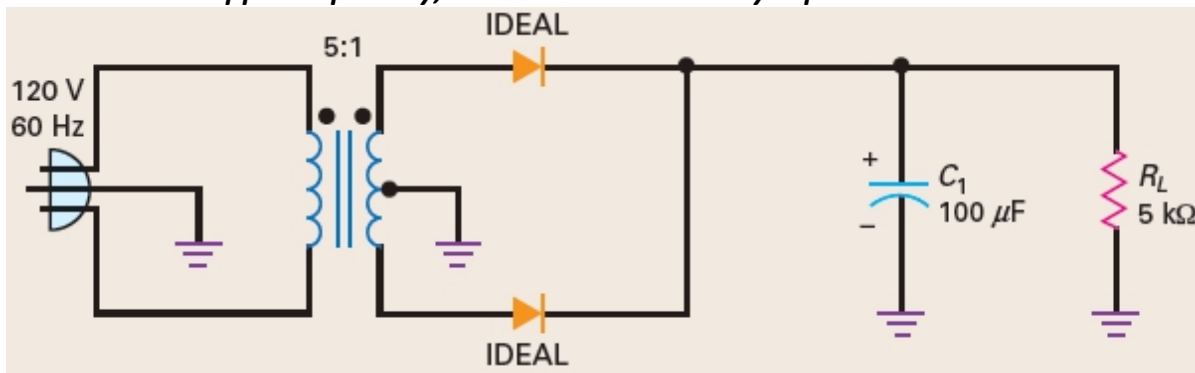
Figure-59 Full-wave rectifier and capacitor-input filter

Example 10

What is the dc load voltage and ripple in Figure-59?

SOLUTION

Since the transformer is 5:1 step-down like the preceding example, the peak secondary voltage is still *34 V*. Half this voltage is the input to each half wave section. Assuming an ideal diode and small ripple, the dc load voltage is:

$$=$$

The dc load current is:

$$= \frac{}{\Omega} = .$$

Now, Eq. (16) gives:

$$= \frac{.}{(\quad)(\quad)} = . \quad - \approx . \quad -$$

Because of the *0.7 V* across the conducting diode, the actual dc load voltage will be closer to *16 V* than to *17 V*.

PRACTICE PROBLEM 7

Using Figure-59, change R_L to *2 kΩ* and calculate the new ideal dc load voltage and ripple.

Example 11

What is the dc load voltage and ripple in Figure-60? Compare the answers with those in the two preceding examples.

SOLUTION

Since the transformer is *5:1* step-down as in the preceding example, the peak secondary voltage is still *34 V*. Assuming an ideal diode and small ripple, the dc load voltage is:
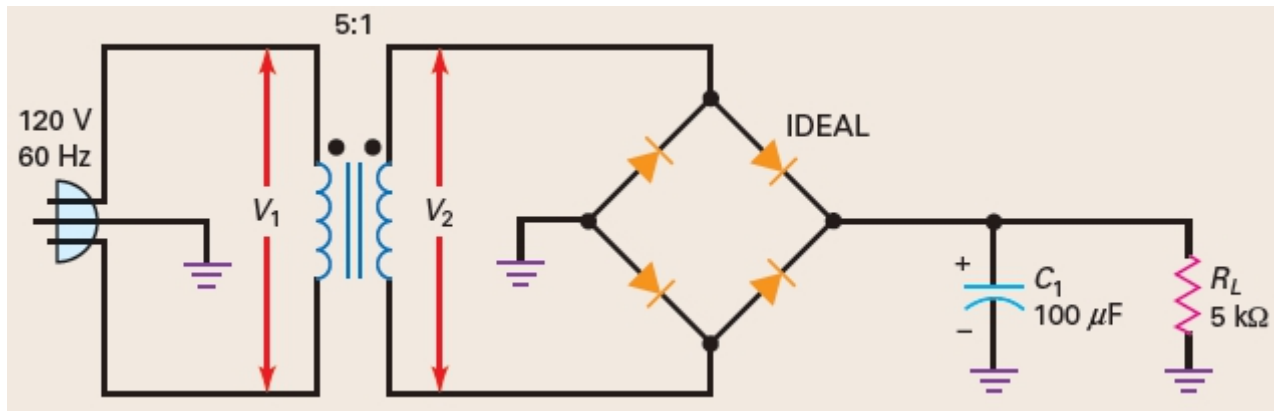
Figure-60 Bridge rectifier and capacitor-input filter

=

The dc load current is:

$$= \frac{}{\Omega} = \ .$$

Now, Eq. (16) gives:

$$= \frac{.}{(\quad)(\quad)} = \ . \quad - \approx \ . \quad -$$

Because of the 1.4 V across two conducting diodes and the ripple, the actual dc load voltage will be closer to 32 V than to 34 V. We have calculated the dc load voltage and ripple for the three different rectifiers. Here are the results:

Half-wave: 34 V and 1.13 V
Full-wave: 17 V and 0.288 V
Bridge: 34 V and 0.566 V

For a given transformer, the bridge rectifier is better than the half-wave rectifier because it has less ripple, and it's better than the full-wave rectifier because it produces twice as much output voltage. Of the three, the bridge rectifier has emerged as the most popular.

1.16 Peak Inverse Voltage and Surge Current

- The peak inverse voltage (PIV) is the maximum voltage across the non-conducting diode of a rectifier. This voltage must be less than the breakdown voltage of the diode; otherwise, the diode will be destroyed.
- The peak inverse voltage depends on the type of rectifier and filter. The worst case occurs with the capacitor-input filter.
- As discussed earlier, data sheets from various manufacturers use many different symbols to indicate the maximum reverse voltage rating of a diode.
- Sometimes, these symbols indicate different conditions of measurement. Some of the data sheet symbols for the maximum reverse voltage rating are *PIV, PRV, V_B, V_{BR}, V_R, V_{RRM}, V_{RWM},* and *$V_{R(max)}$.*

1.16.1 Half-Wave Rectifier with Capacitor-Input Filter

- Figure-61 shows the critical part of a half-wave rectifier. This is the part of the circuit that determines how much reverse voltage is across the diode.
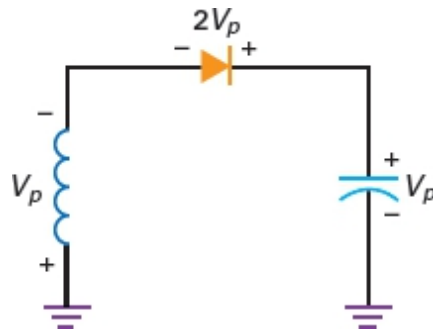
Figure-61 Peak inverse voltage in half-wave rectifier

- The rest of the circuit has no effect and is omitted for the sake of clarity. In the worst case, the peak secondary voltage is on the negative peak and the capacitor is fully charged with a voltage of **Vp**. Apply Kirchhoff's voltage law, and you can see right away that the peak inverse voltage across the non-conducting diode is:

$$= \text{------------------------------- (17)}$$

- For instance, if the peak secondary voltage is **15 V**, the peak inverse voltage is **30 V**. As long as the breakdown voltage of the diode is greater than this, the diode will not be damaged.

1.16.2 Full-Wave Rectifier with Capacitor-Input Filter

- Figure-62 shows the essential part of a full-wave rectifier needed to calculate the peak inverse voltage.
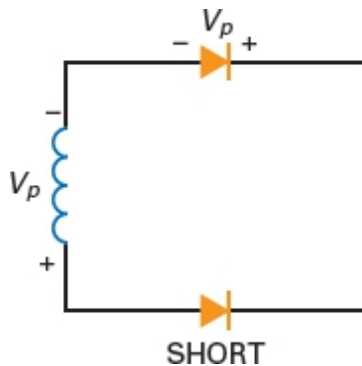
Figure-62 Peak inverse voltage in full-wave rectifier

- Again, the secondary voltage is at the negative peak. In this case, the lower diode acts like a short (closed switch) and the upper diode is open. Kirchhoff's law implies:

$$= \text{------------------------------- (18)}$$

1.16.3 Bridge Rectifier with Capacitor-Input Filter

- Figure-63 shows part of a bridge rectifier. This is all you need to calculate the peak inverse voltage. Since the upper diode is shorted and the lower one is open, the peak inverse voltage across the lower diode is:

$$= \text{------------------------------- (19)}$$

- Another advantage of the bridge rectifier is that it has the lowest peak inverse voltage for a given load voltage. To produce the same load voltage, the full-wave rectifier would need twice as much secondary voltage.
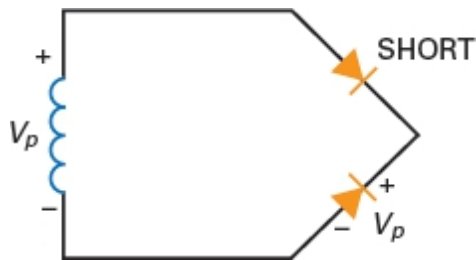
Figure-63 peak inverse voltage in bridge wave rectifier

1.16.4 Surge Resistor

- Before the power is turned on, the filter capacitor is uncharged. At the first instant the power is applied, this capacitor looks like a short. Therefore, the initial charging current may be very large.
- All that exists in the charging path to impede the current is the resistance of the transformer windings and the bulk resistance of the diodes. The initial rush of current when the power is turned on is called the surge current.
- Ordinarily, the designer of the power supply will select a diode with enough current rating to withstand the surge current. The key to the surge current is the size of the filter capacitor.
- Occasionally, a designer may decide to use a surge resistor rather than select another diode.
- Figure-64 illustrates the idea. A small resistor is inserted between the bridge rectifier and the capacitor-input filter.
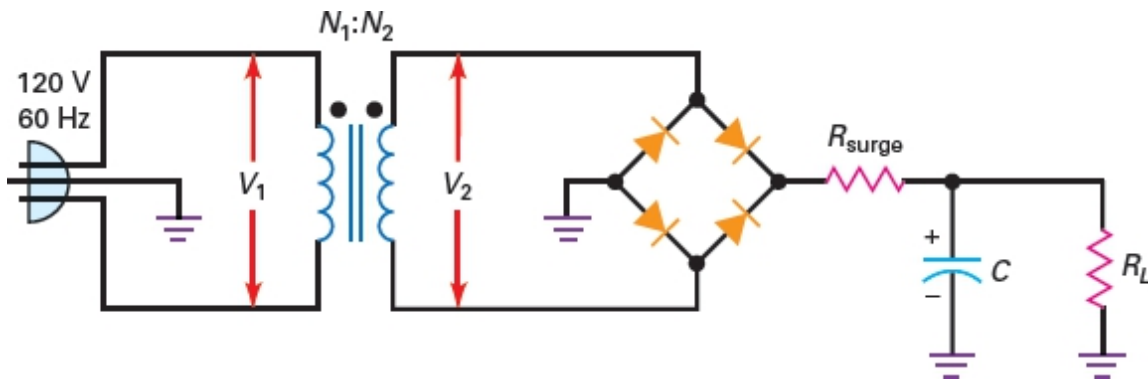
Figure-64 Surge resistor limits surge current

- Without the resistor, the surge current might destroy the diodes. By including the surge resistor, the designer reduces the surge current to a safe level.
- Surge resistors are not used very often and are mentioned just in case you see one used in a power supply.

Example 4-10

What is the peak inverse voltage in Figure-64 if the turn's ratio is **8:1**? A **1N4001** has a breakdown voltage of **50 V**. Is it safe to use a **1N4001** in this circuit?

SOLUTION

The rms secondary voltage is:

$$= \underline{\quad\quad} =$$

The peak secondary voltage is:

$$= \underline{\quad} = \quad.$$

The peak inverse voltage is:

$$= \quad.$$

The **1N4001** is more than adequate, since the peak inverse voltage is much less than the breakdown voltage of **50 V**.

PRACTICE PROBLEM 8

Using Figure-64, change the transformer's turns ratio to 2:1. Which 1N4000 series of diodes should you use?

1.17 Design of Unregulated DC Power-Supply

- You have a basic idea of how power-supply circuits work. In the preceding sections, you have seen how an ac input voltage is rectified and filtered to get a dc voltage. There are a few additional ideas you need to know about.

1.17.1 Commercial Transformers

- The use of turn's ratios with transformers applies only to ideal transformers. Iron core transformers are different. In other words, the transformers you buy from a parts supplier are not ideal because the windings have resistance, which produces power losses.
- Furthermore, the laminated core has eddy currents, which produce additional power losses. Because of these unwanted power losses, the turn's ratio is only an approximation. In fact, the data sheets for transformers rarely list the turn's ratio. Usually, all you get is the secondary voltage at a rated current.
- For instance, Figure-65 shows an F-25X, an industrial transformer whose data sheet gives only the following specifications: for a primary voltage of 115 V ac, the secondary voltage is 12.6 V ac when the secondary current is 1.5 A.

Figure-65 Rating on real transformer

- If the secondary current is less than 1.5 A in Figure-65, the secondary voltage will be more than 12.6 V ac because of lower power losses in the windings and laminated core.
- If it is necessary to know the primary current, you can estimate the turns ratio of a real transformer by using this definition:

$$\underline{\quad} = \underline{\quad}$$

- For instance, the F25X has $V_1 = 115\ V$ and $V_2 = 12.6\ V$. The turns ratio at the rated load current of 1.5 A is:

$$\underline{\quad} = \underline{\quad} = \quad.$$

- This is an approximation because the calculated turn's ratio decreases when the load current decreases.

1.17.2 Calculating Fuse Current

- When troubleshooting, you may need to calculate the primary current to determine whether a fuse is adequate or not. The easiest way to do this with a real transformer is to assume that the input power equals the output power: =

- For instance, Figure-66 shows a fused transformer driving a filtered rectifier. Is the 0.1-A fuse adequate?

- Here is how to estimate the primary current when troubleshooting. The output power equals the dc load power:

$$= \times = (\quad)(. \quad) =$$

- Ignore the power losses in the rectifier and the transformer. Since the input power must equal the output power:

$$=$$

- Since   =   , we can solve for the primary current:

$$= \underline{\quad\quad} = .$$

- This is only an estimate because we ignored the power losses in the transformer and rectifier. The actual primary current will be higher by about **5** to **20** percent because of these additional losses. In any case, the fuse is inadequate. It should be at least 0.25 A.
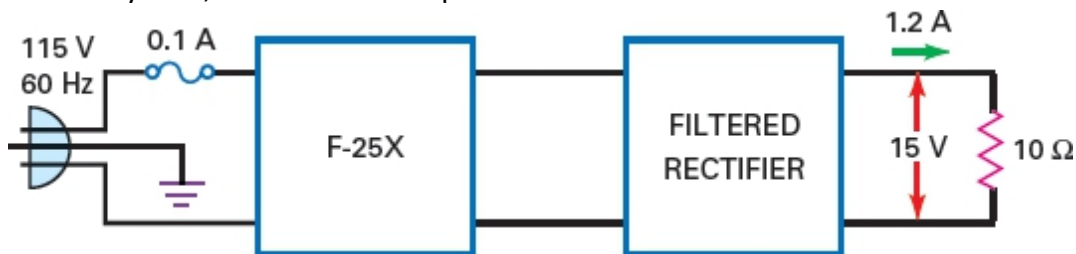
Figure-66 Calculating fuse current

1.17.3 Slow-Blow Fuses

- Assume that a capacitor-input filter is used in Figure-66. If an ordinary 0.25-A fuse is used in Figure-66, it will blow out when you turn the power on. The reason is the surge current, described earlier.

- Most power supplies use a slow-blow fuse, one that can temporarily withstand overloads in current. For instance, a 0.25-A slow-blow fuse can withstand

2 A for 0.1 s
1.5 A for 1 s
1 A for 2 s

And so on. With a slow-blow fuse, the circuit has time to charge the capacitor. Then, the primary current drops down to its normal level with the fuse still intact.

1.17.4 Calculating Diode Current

- Whether a half-wave rectifier is filtered or not, the average current through the diode has to equal the dc load current because there is only one path for current.
- As a derivation:

$$\textit{Half wave:} \quad = \quad \text{-------------------------}(20)$$

- On the other hand, the average current through a diode in the full-wave rectifier equals only half the dc load current because there are two diodes in the circuit, each sharing the load.
- Similarly, each diode in a bridge rectifier has to withstand an average current of half the dc load current. As a derivation:

$$\textit{Full wave:} \quad = \quad . \quad \text{-----------------------}(21)$$

- Summary Table compares the properties of the three capacitor-input filtered rectifiers.

	Half-wave	Full-wave	Bridge
Number of diodes	1	2	4
Rectifier input	$V_{p(2)}$	$0.5V_{p(2)}$	$V_{p(2)}$
DC output (ideal)	$V_{p(2)}$	$0.5V_{p(2)}$	$V_{p(2)}$
DC output (2d)	$V_{p(2)} - 0.7\text{ V}$	$0.5V_{p(2)} - 0.7\text{ V}$	$V_{p(2)} - 1.4\text{ V}$
Ripple frequency	f_{in}	$2f_{in}$	$2f_{in}$
PIV	$2V_{p(2)}$	$V_{p(2)}$	$V_{p(2)}$
Diode current	I_{dc}	$0.5I_{dc}$	$0.5I_{dc}$

*Vp(2) = Peak secondary voltage; Vp(out) = Peak output voltage; I_{dc} = dc load current.

1.17.5 RC Filters

- Before the 1970s, passive filters (R, L, and C components) were often connected between the rectifier and the load resistance. Nowadays, you rarely see passive filters used in semiconductor power supplies, but there might be special applications, such as audio power amplifiers, in which you might encounter them.
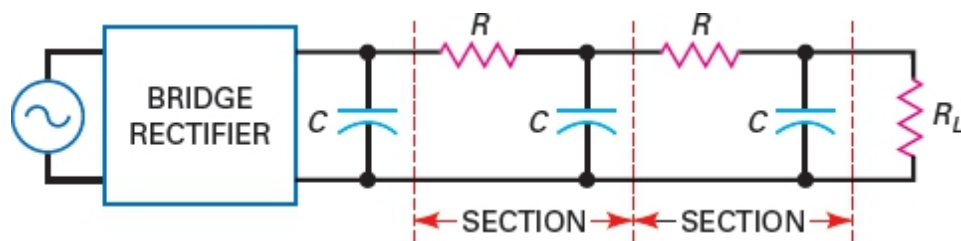

Figure-67 RC filtering

- Figure-67 shows a bridge rectifier and a capacitor-input filter. Usually, a designer will settle for a peak-to-peak ripple of as much as 10 percent across the filter capacitor. The reason for not trying

to get even lower ripple is because the ***filter capacitor would become too large***. Additional filtering is then done by RC sections between the filter capacitor and the load resistor.

- The RC sections are examples of a passive filter, one that uses only **R, L,** or **C** components. By deliberate design, R is much greater than X_C at the ripple frequency. Therefore, the ripple is reduced before it reaches the load resistor.
- Typically, **R** is at least **10** times greater than X_C. This means that each section attenuates (reduces) the ripple by a factor of at least **10**.
- The disadvantage of an **RC** filter is the loss of dc voltage across each **R**. Because of this, the **RC** filter is suitable only for very light loads (small load current or large load resistance).

1.17.6 LC Filter

- When the load current is large, the **LC** filters of Figure-68 are an improvement over **RC** filters. Again, the idea is to drop the ripple across the series components, in this case, the inductors. By making X_L much greater than X_C, we can reduce the ripple to a very low level.
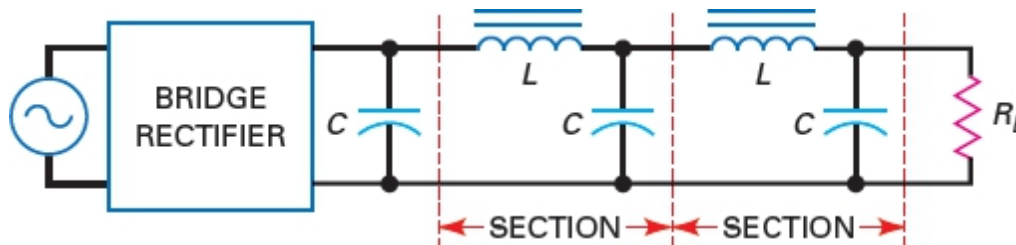

Figure-68 LC Filtering

- The dc voltage drop across the inductors is much smaller than it is across the resistors of **RC** sections because the winding resistance is smaller.
- The **LC** filter was very popular at one time. Now, it's becoming obsolete in typical power supplies because of the size and cost of inductors. For low-voltage power supplies, the **LC** filter has been replaced by an integrated circuit (**IC**).
- This is a device that contains diodes, transistors, resistors, and other components in a miniaturized package to perform a specific function.
- Figure-69 illustrates the idea. An IC voltage regulator, one type of integrated circuit, is between the filter capacitor and the load resistor. This device not only reduces the ripple, it also holds the output voltage constant.

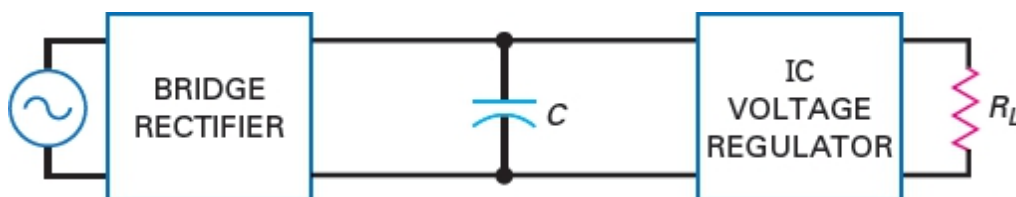**Figure-69 Voltage-regulator filtering**

- Figure-70 shows an example of a three-terminal voltage regulator. The **LM7805** IC provides for a five-volt fixed ***positive*** output voltage, as long as the input voltage to the **IC** is at least 2 to 3 volts greater than the required output voltage.
- Other regulators in the **78XX** series can regulate a range of output values, such as 9 V, 12 V, and 15 V.

- The **79XX** series provides regulated **negative** output values. Because of their low cost, IC voltage regulators are now the standard method used for ripple reduction.
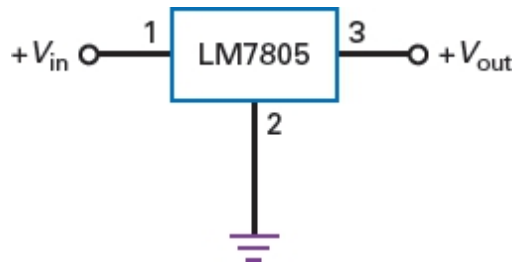

Figure-70 Three-terminal voltage regulator

1.18 Clippers and Limiters

- The diodes used in low-frequency power supplies are rectifier diodes. These diodes are optimized for use at **60 Hz** and have power ratings greater than **0.5 W**.
- The typical rectifier diode has a forward current rating in amperes. Except for power supplies, rectifier diodes have little use because most circuits inside electronics equipment are running at much higher frequencies.

1.18.1 Small-Signal Diodes

- In this section, we will be using small-signal diodes. These diodes are optimized for use at high frequencies and have power ratings less than **0.5 W**. The typical small-signal diode has a current rating in milli-amperes.
- It is this smaller and lighter construction that allows the diode to work at higher frequencies.

1.18.2 The Positive Clipper

- A clipper is a circuit that removes either positive or negative parts of a waveform. This kind of processing is useful for signal shaping, circuit protection, and communications.
- Figure-71a shows a positive clipper. The circuit removes all the positive parts of the input signal. This is why the output signal has only negative half-cycles.
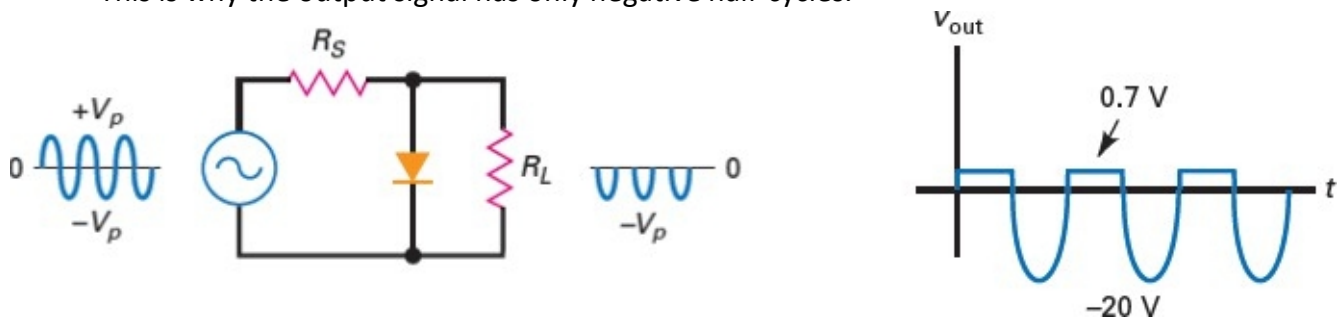
Figure-71 (a) Positive clipper; (b) output waveform

- Here is how the circuit works: During the positive half-cycle, the diode turns on and looks like a short across the output terminals. Ideally, the output voltage is zero. On the negative half-cycle, the diode is open. In this case, a negative half-cycle appears across the output.
- By deliberate design, the series resistor is much smaller than the load resistor. This is why the negative output peak is shown as **2Vp** in Figure-71a.

- To a second approximation, the diode voltage is 0.7 V when conducting. Therefore, the clipping level is not zero, but 0.7 V. For instance, if the input signal has a peak value of **20 V**, the output of the clipper will look like Figure-71b.

1.18.3 Defining Conditions

- Small-signal diodes have a smaller junction area than rectifier diodes because they are optimized to work at higher frequencies. As a result, they have more bulk resistance. The data sheet of a small-signal diode like the **1N914** lists a forward current of **10 mA** at **1 V**. Therefore, the bulk resistance is:

$$= \frac{-\ .}{\ } = \quad \Omega$$

- Why is bulk resistance important? Because the clipper will not work properly unless the series resistance **RS** is much greater than the bulk resistance.
- Furthermore, the clipper won't work properly unless the series resistance **RS** is much smaller than the load resistance. For a clipper to work properly, we will use this definition:

$$: \qquad < \qquad < \ . \qquad \text{----------------------------- (22)}$$

- This says that the series resistance must be 100 times greater than the bulk resistance and 100 times smaller than the load resistance. When a clipper satisfies these conditions, we call it a stiff clipper.
- For instance, if the diode has a bulk resistance of 30 Ω, the series resistance should be at least 3 kΩ and the load resistance should be at least 300 kΩ.

1.18.4 The Negative Clipper

- If we reverse the polarity of the diode as shown in Figure-72a, we get a negative clipper. As you would expect, this removes the negative parts of the signal. Ideally, the output waveform has nothing but positive half-cycles.
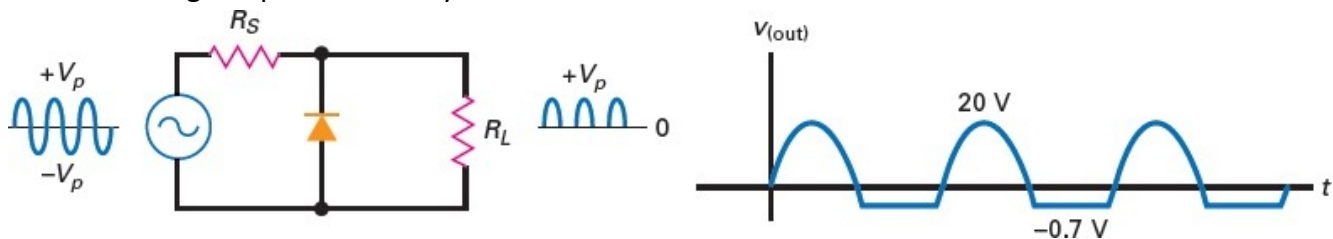

Figure-72 (a) Negative clipper; (b) output waveform

- The clipping is not perfect. Because of the diode offset voltage (another way of saying barrier potential), the clipping level is at **20.7 V**. If the input signal has a peak of 20 V, the output signal will look like Figure-72b.

1.18.5 The Limiter or Diode Clamp

- The clipper is useful for wave-shaping, but the same circuit can be used in a totally different way. Take a look at Figure-73a. The normal input to this circuit is a signal with a peak of only 15 mV.
- Therefore, the normal output is the same signal because neither diode is turned during the cycle. What good is the circuit if the diodes don't turn on? Whenever you have a sensitive circuit, one

that cannot have too much input, you can use a positive-negative limiter to protect its input, as shown in Figure-73b. If the input signal tries to rise above 0.7 V, the output is limited to 0.7 V.
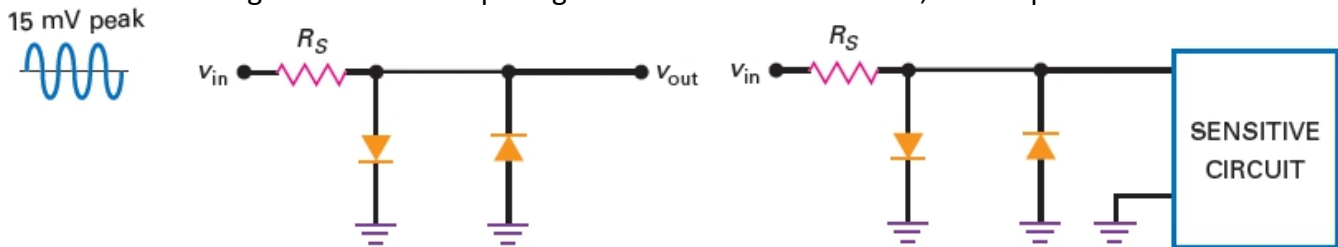

Figure-73 (a) Diode clamp; (b) protecting a sensitive circuit

- On the other hand, if the input signal tries to drop below 20.7 V, the output is limited to 20.7 V. In a circuit like this, normal operation means that the input signal is always smaller than 0.7 V in either polarity.
- A more familiar example of a sensitive circuit is a moving-coil meter. By including a limiter, we can protect the meter movement against excessive input voltage or current.
- The limiter of Figure-73a is also called a diode clamp. The term suggests clamping or limiting the voltage to a specified range. With a diode clamp, the diodes remain off during normal operation. The diodes conduct only when something is abnormal, when the signal is too large.

1.18.6 Biased Clippers

- The reference level (same as the clipping level) of a positive clipper is ideally zero, or 0.7 V to a second approximation. What can we do to change this reference level?
- In electronics, bias means applying an external voltage to change the reference level of a circuit. Figure-74a is an example of using bias to change the reference level of a positive clipper.
- By adding a dc voltage source in series with the diode, we can change the clipping level. The new **V** must be less than **Vp** for normal operation. With an ideal diode, conduction starts as soon as the input voltage is greater than **V**.
- To a second approximation, it starts when the input voltage is greater than **V + 0.7 V**.
- Figure-74b shows how to bias a negative clipper. Notice that the diode and battery have been reversed. Because of this, the reference level changes to **−V − 0.7 V**. The output waveform is negatively clipped at the bias level.

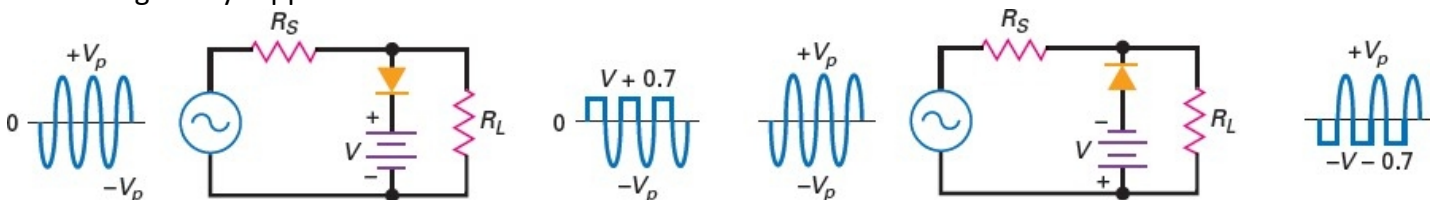**Figure-74 (a) Biased positive clipper; (b) biased negative clipper**

1.18.7 Combination Clipper

- We can combine the two biased clippers as shown in Figure-75. Diode **D₁** clips off positive parts above the positive bias level, and diode **D₂** clips off parts below the negative bias level.
- When the input voltage is very large compared to the bias levels, the output signal is a square wave, as shown in Figure-75.

- This is another example of the signal shaping that is possible with clippers.
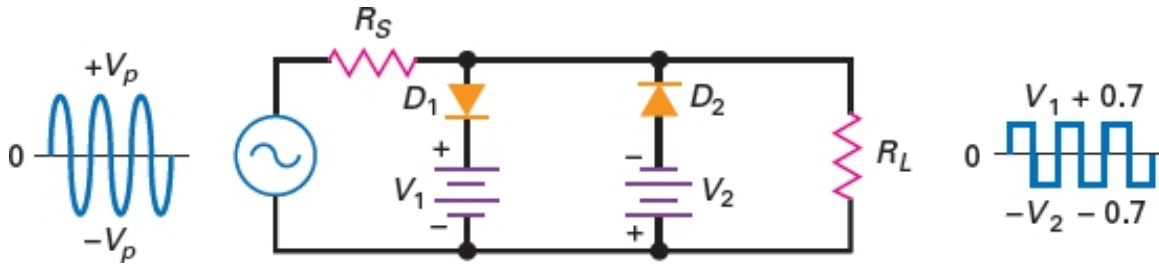

Figure-75 Biased positive-negative clipper

1.18.8 Variations

- Using batteries to set the clipping level is impractical. One approach is to add more silicon diodes because each produces a bias of 0.7 V. For instance, Figure-76a shows three diodes in a positive clipper.
- Since each diode has an offset of around 0.7 V, the three diodes produce a clipping level of approximately +2.1 V. The application does not have to be a clipper (wave-shaping). We can use the same circuit as a diode clamp (limiting) to protect a sensitive circuit that cannot tolerate more than a 2.1 V input.
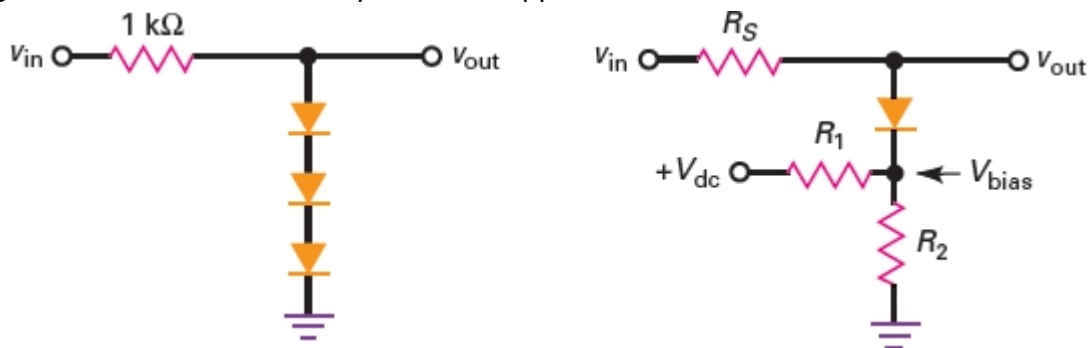- Figure-76b shows another way to bias a clipper without batteries.

Figure-76 (a) Clipper using three-diode off set; (b) Voltage divider biases clipper

- This time, we are using a voltage divider (R1 and R2) to set the bias level. The bias level is given by:

$$= \frac{\quad}{+} \quad \text{-- (23)}$$

- In this case, the output voltage is clipped or limited when the input is greater than $V_{bias} + 0.7V$.
- Figure-77 a shows a biased diode clamp. It can be used to protect sensitive circuits from excessive input voltages. The bias level is shown as +5 V.
- It can be any bias level you want it to be. With a circuit like this, a destructively large voltage of +100 V never reaches the load because the diode limits the output voltage to a maximum value of +5.7 V.
- Sometimes a variation like Figure-77b is used to remove the offset of the limiting diode D_1. Here is the idea: Diode D_2 is biased slightly into forward conduction so that it has approximately 0.7 V across it.
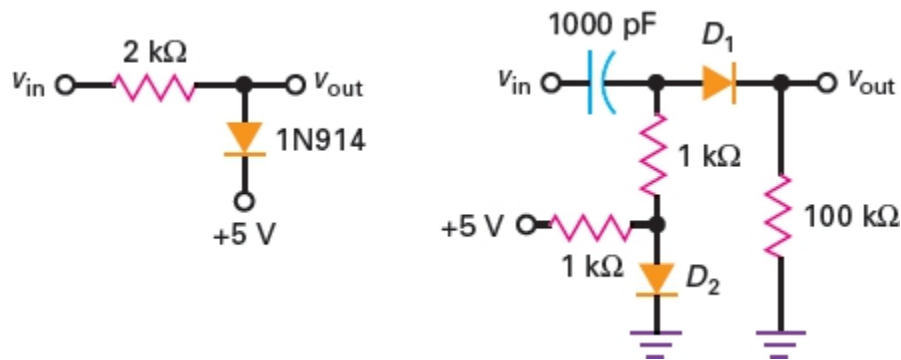
Figure-77 (a) diode clamp protects above 5.7 V; (b) diode D2 biases D1 to remove off set voltage

- This 0.7 V is applied to 1 kΩ in series with D1 and 100 kΩ. This means that diode D_1 is on the verge of conduction. Therefore, when a signal comes in, diode D_1 conducts near 0 V.

1.19 Clampers

- The diode clamp, which was discussed in the preceding section, protects sensitive circuits. The clamper is different, so don't confuse the similar-sounding names. A clamper adds a dc voltage to the signal.

1.19.1 Positive Clamper

- Figure-78a shows the basic idea for a positive clamper. When a positive clamper has a sine-wave input, it adds a positive dc voltage to the sine wave.
- Stated another way, the positive clamper shifts the ac reference level (normally zero) up to a dc level.
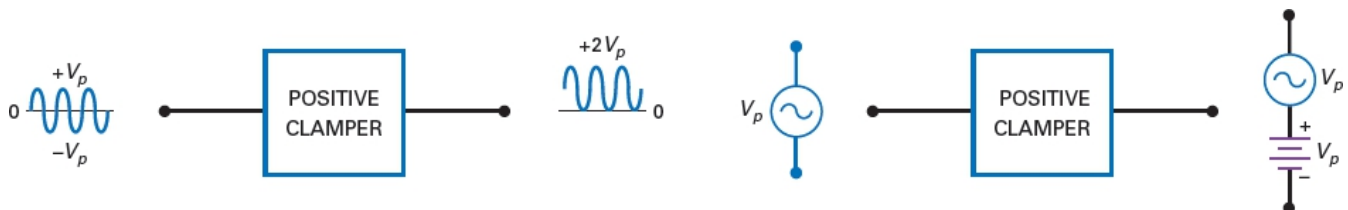

Figure-78 (a) Positive clamper shifts waveform upward; (b) positive clamper adds a dc component to signal

- The effect is to have an ac voltage centered on a dc level. This means that each point on the sine wave is shifted upward, as shown on the output wave.
- Figure-78b shows an equivalent way of visualizing the effect of a positive clamper. An ac source drives the input side of the clamper. The Thevenin voltage of the clamper output is the superposition of a dc source and an ac source.
- The ac signal has a dc voltage of Vp added to it. This is why the entire sine wave of Figure-78a has shifted upward so that it has a positive peak of $2Vp$ and a negative peak of zero.
- Figure-79a is a positive clamper. Ideally, here is how it works. The capacitor is initially uncharged. On the first negative half-cycle of input voltage, the diode turns on (Figure-79b). At the negative peak of the ac source, the capacitor has fully charged and its voltage is Vp with the polarity shown.
- Slightly beyond the negative peak, the diode shuts off (Figure-79c). The RLC time constant is deliberately made much larger than the period T of the signal.
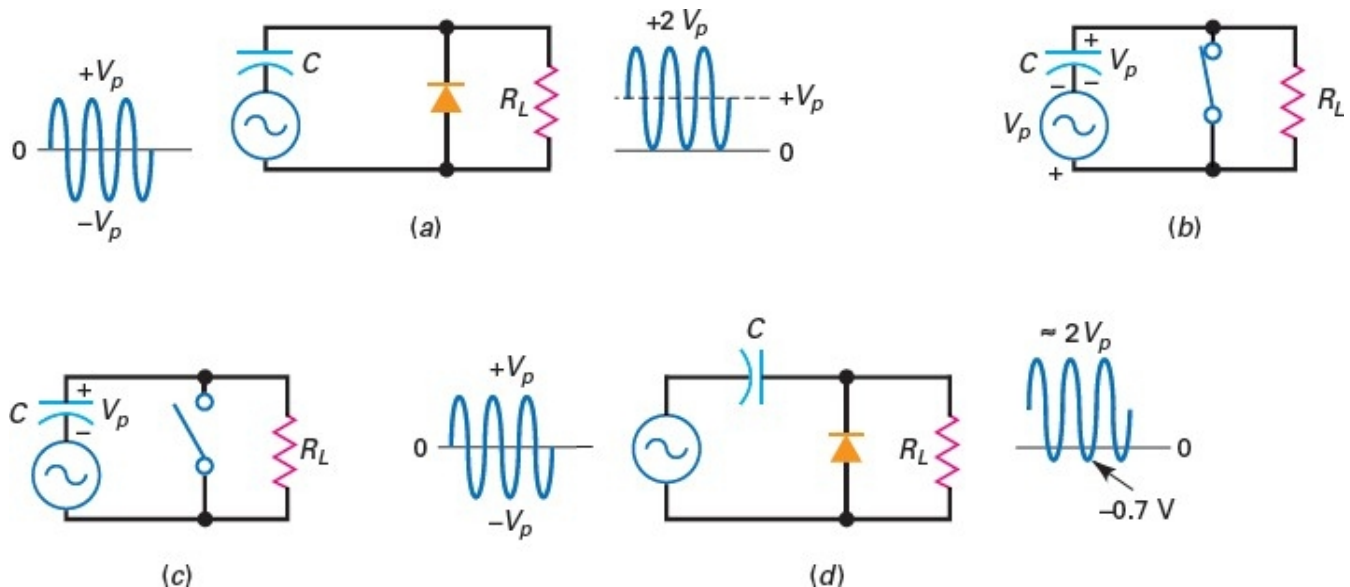
Figure-79 (a) Ideal positive clamper; (b) at the positive peak (c) beyond the positive peak; (d) clamper is not quite perfect

- We will define much larger as at least 100 times greater:

$$: \quad > \quad \text{--} \quad (24)$$

- For this reason, the capacitor remains almost fully charged during the off time of the diode. To a first approximation, the capacitor acts like a battery of **Vp** volts.
- This is why the output voltage in Figure-79a is a positively clamped signal. Any clamper that satisfies Eq. (24) is called a stiff clamper.
- The idea is similar to the way *a half-wave rectifier with a capacitor-input filter works*. The first quarter-cycle charges the capacitor fully. Then, the capacitor retains almost all of its charge during subsequent cycles. The small charge that is lost between cycles is replaced by diode conduction.
- In Figure-79c, the charged capacitor looks like a battery with a voltage of **Vp**. This is the dc voltage that is being added to the signal. After the first quarter cycle, the output voltage is a positively clamped sine wave with a reference level of zero; that is, it sits on a level of **0 V**.
- Figure-79d shows the circuit as it is usually drawn. Since the diode drops 0.7 V when conducting, the capacitor voltage does not quite reach **Vp**. For this reason, the clamping is not perfect, and the negative peaks have a reference level of **− 0.7V**.

1.19.2 Negative Clamper

- What happens if we turn the diode in Figure-79d around? We get the negative clamper of Figure-80. As you can see, the capacitor voltage reverses, and the circuit becomes a negative clamper.
- Again, the clamping is less than perfect because the positive peaks have a reference level of **0.7V** instead of **0 V**. As a memory aid, notice that the diode points in the direction of shift.
- In Figure-80, the diode points downward, the same direction as the shift of the sine wave. This tells you that it's a negative clamper. In Figure-79a, the diode points up, the waveform shifts up, and you have positive clamper.
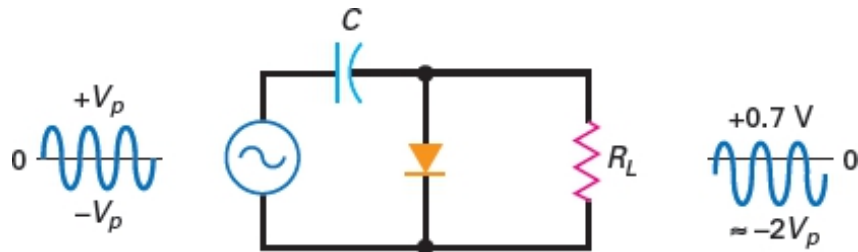
Figure-80 Negative clamper

- Both positive and negative clampers are widely used. For instance, television receivers use a clamper to change the reference level of video signals. Clampers are also used in radar and communication circuits.

1.19.3 Peak-to-Peak Detector

- A half-wave rectifier with a capacitor-input filter produces a dc output voltage approximately equal to the peak of the input signal. When the same circuit uses a small-signal diode, it is called a peak detector.
- Typically, peak detectors operate at frequencies that are much higher than 60 Hz. The output of a peak detector is useful in measurements, signal processing, and communications.
- If you cascade a clamper and a peak detector, you get a peak-to-peak detector (see Figure-81). As you can see, the output of a clamper is used as the input to a peak detector.
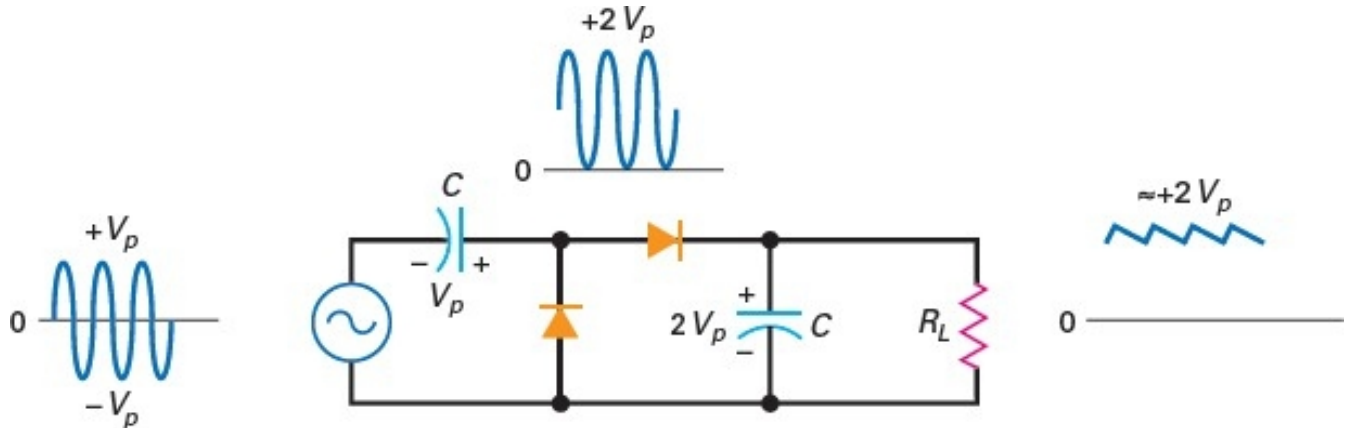

Figure-81 Peak-to-peak detector

- Since the sine wave is positively clamped, the input to the peak detector has a peak value of *2Vp*. This is why the output of the peak detector is a dc voltage equal to *2Vp*.
- As usual, the RC time constant must be much greater than the period of the signal. By satisfying this condition, you get good clamping action and good peak detection. The output ripple will therefore be small.
- One application is in measuring non-sinusoidal signals. An ordinary ac voltmeter is calibrated to read the rms value of an ac signal. If you try to measure a non-sinusoidal signal, you will get an incorrect reading with an ordinary ac voltmeter.
- However, if the output of a peak-to-peak detector is used as the input to a dc voltmeter, it will indicate the peak-to-peak voltage. If the non-sinusoidal signal swings from **− 20 to + 50 V**, the reading is **70 V**.

1.20 Voltage Multipliers

- A peak-to-peak detector uses small-signal diodes and operates at high frequencies. By using rectifier diodes and operating at 60 Hz, we can produce a new kind of power supply called a voltage doubler.

1.20.1 Voltage Doubler

- Figure-82 is a voltage doubler. The configuration is the same as a peak-to-peak detector, except that we use rectifier diodes and operate at 60 Hz.
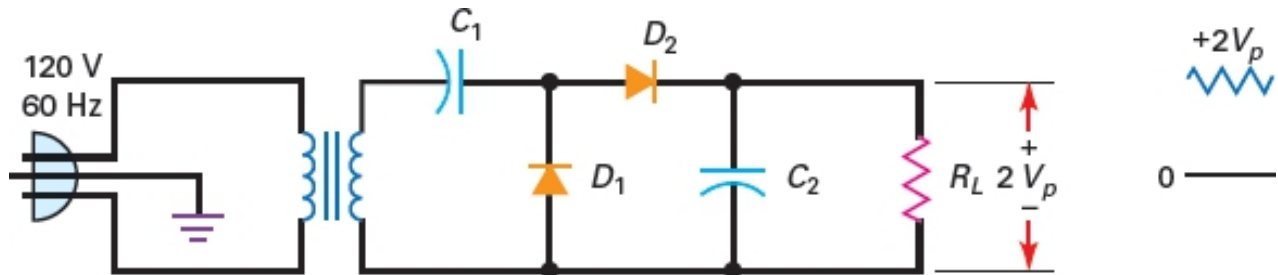

Figure-82 Voltage Doubler

- The clamper section adds a dc component to the secondary voltage. The peak detector then produces a dc output voltage that is two times the secondary voltage.
- Why bother using a voltage doubler when you can change the turn's ratio to get more output voltage?
- The answer is that you don't need to use a voltage doubler at lower voltages. The only time you run into a problem is when you are trying to produce very high dc output voltages.
- For instance, line voltage is **120 V** rms, or **170 V** peak. If you are trying to produce 3400 V dc, you will need to use a **1:20** step-up transformer.
- Here is where the problem comes in. Very high secondary voltages can be obtained only with bulky transformers. At some point, a designer may decide that it would be simpler to use a voltage doubler and a smaller transformer.

1.20.2 Voltage Tripler

- By connecting another section, we get the voltage Tripler of Figure-83. The first two sections act like a doubler.
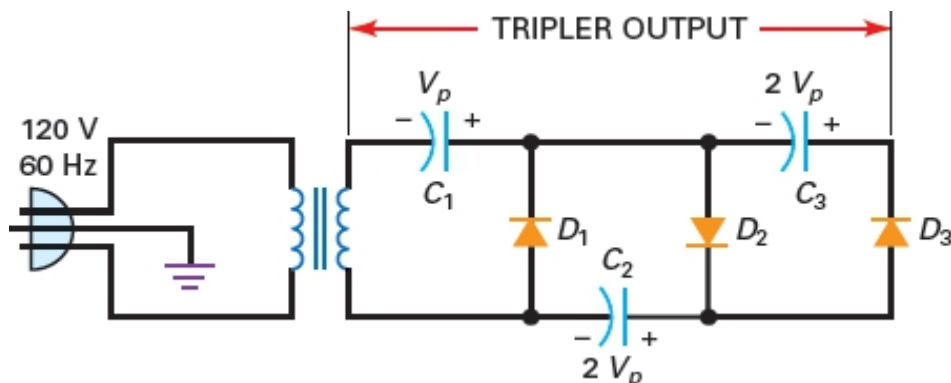

Figure-83 Voltage Tripler

- At the peak of the negative half-cycle, D_3 is forward biased. This charges C_3 to $2Vp$ with the polarity shown in Figure-83.
- The tripler output appears across C_1 and C_3. The load resistance can be connected across the tripler output. As long as the time constant is long, the output equals approximately $3\,Vp$.

1.20.3 Voltage Quadrupler

- Figure-84 is a voltage quadrupler with four sections in cascade (one after another). The first three sections are a tripler, and the fourth makes the overall circuit a quadrupler.
- The first capacitor charges to Vp. All others charge to $2Vp$. The quadrupler output is across the series connection of C_2 and C_4. We can connect a load resistance across the quadrupler output to get an output of $4Vp$.

Figure-84 Voltage Quadrupler
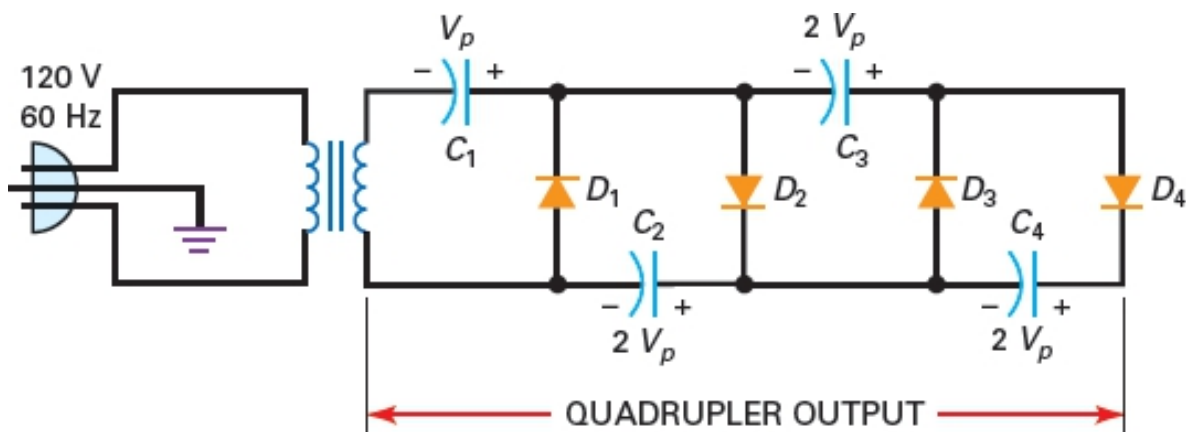
- Theoretically, we can add sections indefinitely, but the ripple gets much worse with each new section.
- Increased ripple is another reason why voltage multipliers (doublers, triplers, and quadruplers) are not used in low-voltage power supplies.
- As stated earlier, voltage multipliers are almost always used to produce high voltages, well into the hundreds or thousands of volts. Voltage multipliers are the natural choice for high-voltage and low-current devices like the cathode-ray tube (CRT) used in television receivers, oscilloscopes, and computer monitors.

1.20.4 Variations

- All of the voltage multipliers shown in Figures 82, 83 and 84 use load resistances that are floating. This means that neither end of the load is grounded.
- Figures-85a, b, and c show variations of the voltage multipliers. Figure-85a merely adds grounds to Figure-82.
- On the other hand, Figures-85b and c are redesigns of the tripler (Figure-83) and quadrupler (figure-84). In some applications, you may see floating-load designs used (such as in the CRT); in others, you may see the grounded-load designs used.
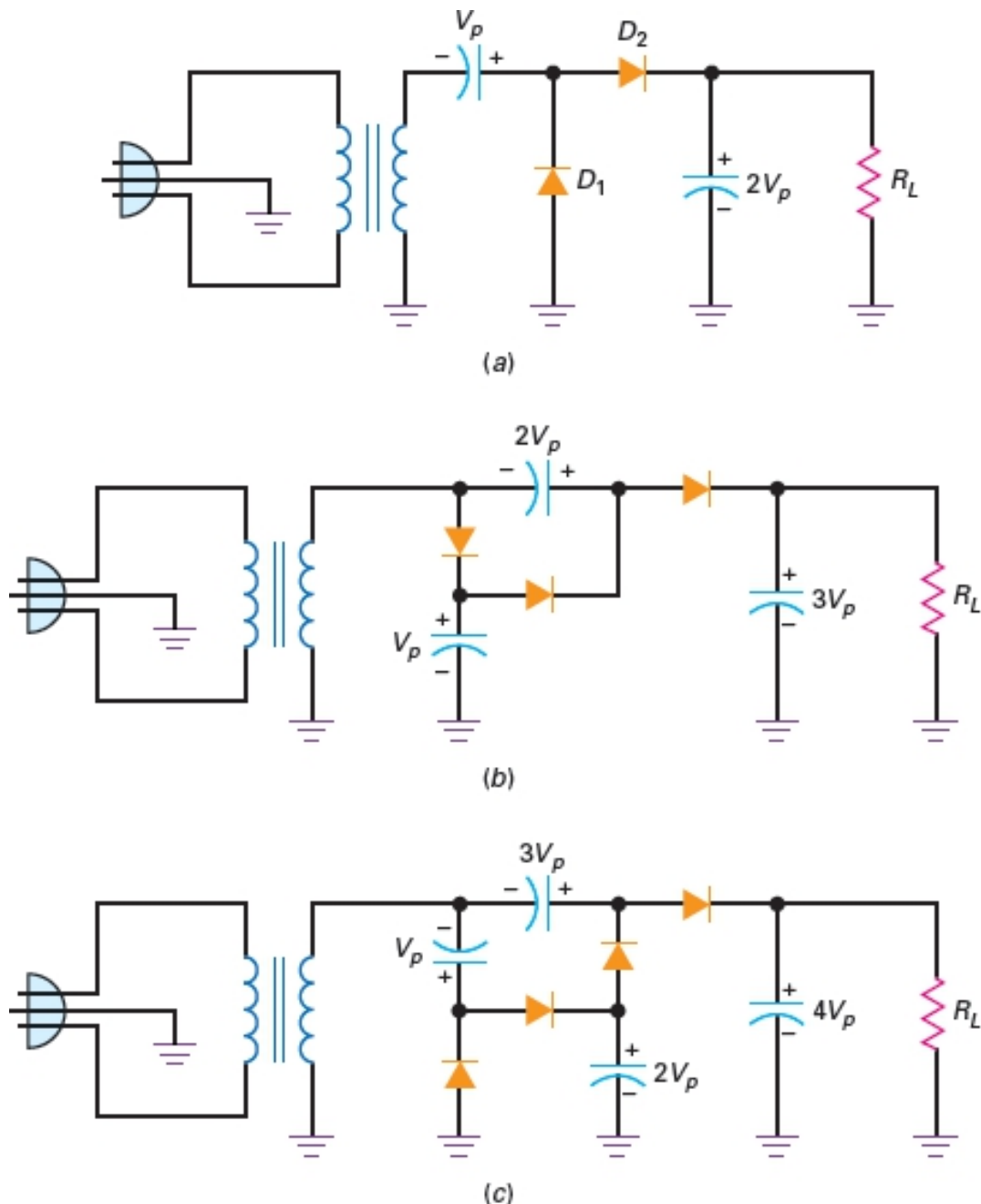
Figure-85 Voltage multipliers with grounded loads (a) Doubler; (b) tripler; (c) quadrupler

1.20.5 Full-Wave Voltage Doubler

- Figure-86 shows a full-wave voltage doubler. On the positive half-cycle of the source, the upper capacitor charges to the peak voltage with the polarity shown. On the next half-cycle, the lower capacitor charges to the peak voltage with the indicated polarity.
- For a light load, the final output voltage is approximately **2Vp**. The voltage multipliers discussed earlier are half-wave designs; that is, the output ripple frequency is 60 Hz.
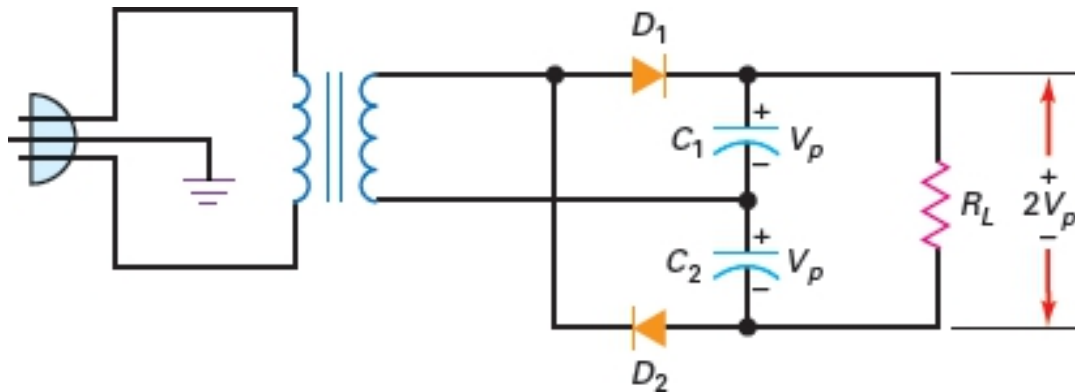
Figure-86 full-wave doubler

- On the other hand, the circuit of Figure-86 is called a full-wave voltage doubler because one of the output capacitors is being charged during each half-cycle. Because of this, the output ripple is 120 Hz.
- This ripple frequency is an advantage because it is easier to filter.
- Another advantage of the full-wave doubler is that the **PIV** rating of the diodes need only be greater than **Vp**.

1.21 Question Bank

1) Explain following terms:
   a. Unbiased Diode
   b. The Depletion Layer
   c. Barrier Potential
2) **Explain V-I characteristic of P N junction. (Most IMP)**
   OR
   Explain V-I characteristic of normal rectifier diode. (Most IMP)
   OR
   Explain V-I characteristic of Avalanche diode. (Most IMP)
3) Describe first (ideal), second & third approximations of diode.
4) Describe how to troubleshoot diode with the help of multimeter.
5) Write a short note on Surface Mount Diodes.
6) Describe the circuit that produce half output with circuit diagram, waveforms and required derivations.
   OR
   Explain half wave rectifier with circuit diagram, waveforms and required derivations.
7) Describe the circuit that uses center tape transformer for rectification with circuit diagram, waveforms and required derivations.
   OR
   Explain full wave rectifier with center tape transformer using circuit diagram, waveforms and required derivations.
   OR

Describe the circuit that uses two diodes for full wave rectification with circuit diagram, waveforms and required derivations.

8) **Describe the circuit that suits best for rectification with circuit diagram, waveforms and required derivations. (Most IMP)**

    OR

    Explain bridge rectifier using circuit diagram, waveforms and required derivations. (Most IMP)

    OR

    Describe the circuit that uses four diodes for full wave rectification with circuit diagram, waveforms and required derivations. (Most IMP)

9) Describe choke and capacitor input filter with its advantages and disadvantages.

10) Explain all steps for design of unregulated DC power supply.

11) **Explain all types (biased/unbiased) of clipper/limiter circuits with appropriate waveforms.(Most IMP)**

12) Explain diode clamp circuits used for protection purpose.

13) Describe all types of clamper circuits.

14) Explain voltage multiplier circuits in detail.