# RECTIFYING CIRCUITS

Almost all electronic circuits need to utilize direct current (dc) sources of power for operation. Hand-held and portable electronic equipment use replenishable or rechargeable batteries as their main source of power. Normally, a *power supply* provides energy for all other electronic equipment. A power supply is composed of electronic circuitry that essentially converts alternating current to direct current. Electronic circuits designed to accomplish this conversion are known as *rectifying circuits* (see Table 1). They are classified into three major categories:

Half-wave rectifier (HWR)
Full-wave rectifier (FWR)
Bridge rectifier

**Table 1. Comparison of the Three Rectifier Circuits**

| | Half-Wave | Full-Wave | Bridge |
|---|---|---|---|
| Number of diodes | One | Two | Four |
| Peak line voltage | $V_m$ | $V_m$[a] | $V_m$ |
| rms line voltage | $V_m/\sqrt{2}$ | $V_m/\sqrt{2}$ | $V_m/\sqrt{2}$ |
| Peak inverse voltage | $V_m$ | $2V_m$ | $V_m$ |
| dc output voltage | $0.318V_m$ | $0.636V_m$ | $0.636V_m$ |
| Ratio of rectification | 0.406 | 0.812 | 0.812 |
| Transformer utilization factor | 0.287 | 0.693[b] | 0.812 |
| Ripple frequency | $f$ | $2f$ | $2f$ |
| Ripple factor | 1.21 | 0.482 | 0.482 |

[a] One-half the secondary coil voltage.
[b] Average of primary and secondary coils.

At the present time, the silicon diode is the most commonly used electronic device for rectification purposes. Semiconductor diodes have replaced previously used devices such as vacuum tube diodes and dry-disk or metallic rectifiers. Figures 1(a) and 1(b) show the constructional features of four types of rectifiers that can be used to accomplish the task of converting alternating current (ac) to dc. The principle of rectification is to permit current flow in one direction only. The diode is capable of accomplishing this task because it conducts only when it is *forward biased.* This means that the anode or the *positive electrode* of the diode receives positive voltage. When the cathode or the *negative electrode* is connected to the positive supply terminal, the diode is *reverse biased.* Thereby the diode can be used in an appropriate circuit, called a *rectifier circuit,* to convert an alternating waveform to a unidirectional waveform. While discussing rectifier circuits throughout this article a sinusoidal waveform is considered as input, for convenience of mathematical treatment.

A rectifying circuit is normally used in conjunction with a transformer, filter, and a voltage regulator. Figure 2 shows a block diagram representation of a power supply. The transformer reduces or increases the amplitude of the ac voltage so that appropriate dc magnitude is obtained after rectification filteration and regulation. In addition, the transformer provides electrical isolation that may be necessary. The rectifier circuit converts the sinusoidal output of the transformer to a unidirectional pulsating dc signal. The filter circuit “fills in” the valleys of the pulsating dc signal output of the rectifier and strives to accomplish a “smooth” dc output. The voltage regulator tries to maintain a constant output voltage regardless of the fluctuations in the input ac signal and the output dc load current consumption. Main equations pertaining to the three rectifier circuits can be found in the Appendix 1, 2, and 3.

## HALF-WAVE RECTIFIER CIRCUIT

The basic action of a simple half-wave rectifier circuit with a resistive load can be examined using a circuit shown in Fig. 3(a). A semiconductor diode, a load resistor, and the secondary coil of a transformer are connected in series. The primary coil of the transformer receives the ac input supply. Let the output voltage of the transformer secondary coil be represented as $v_i = V_m \sin \omega t$ where $v_i$ is the instantaneous value of the voltage and $V_m$ is the peak value. Furthermore, let us assume that the forward voltage drop of the diode is very small (0.7 V for silicon and 0.3 V for germanium) compared to the input signal. We find the relation $i = i_d = i_R$, where $i$ is the current in the transformer secondary coil closed circuit, $i_d$ is the diode current, and $i_R$ is the current in the resistance $R$. The diode offers a resistance $R_f$ while conducting in the “on” state and offers infinite resistance while not conducting in the “off” state. Therefore, mathematically speaking, the half-wave rectifier obeys the following equations:

$$i = \begin{cases} i_d = i_R = I_m \sin \omega t & \text{if } 0 \le \omega t \le \pi \\ 0 & \text{if } \pi \le \omega t \le 2\pi \end{cases}$$

where $I_m = V_m/(R_f + R)$.

Figures 3(b) and 3(c) represent the input and output waveforms. It is observed that the output load resistance experiences only one half cycle for every one full cycle of input waveform. The average value of one full cycle of the input waveform can easily be computed to be equal to zero. Similarly, the average value of the output dc current can be calculated by considering one full cycle of the output waveform. It needs to be recognized that the output waveform is only one half cycle of the sine wave input. This is because the negative half of the input waveform is not admitted to pass through

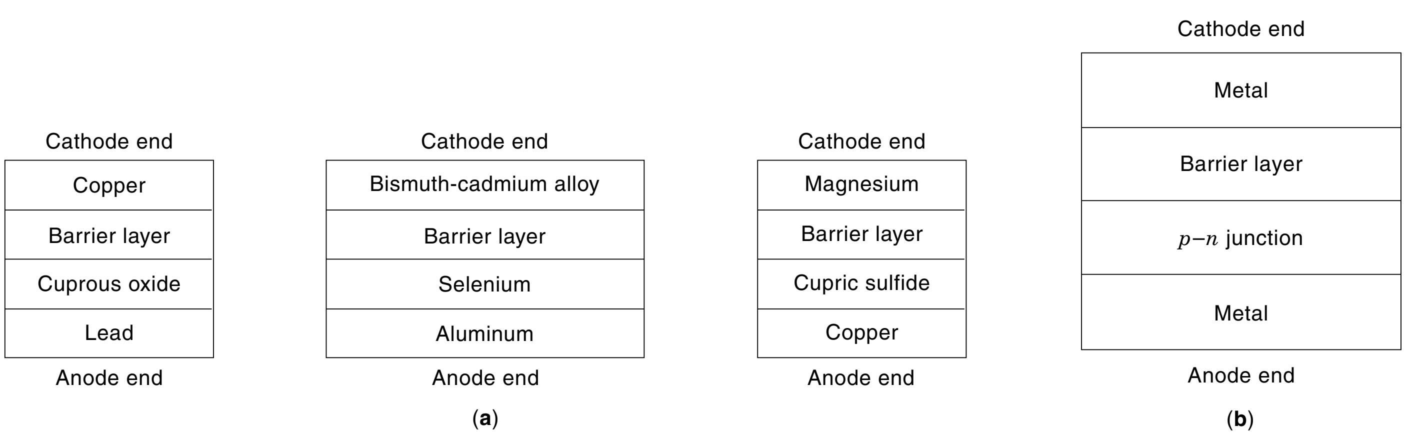


**Figure 1.** Salient features of (a) metallic rectifiers and (b) a semiconductor diode (both not to scale).

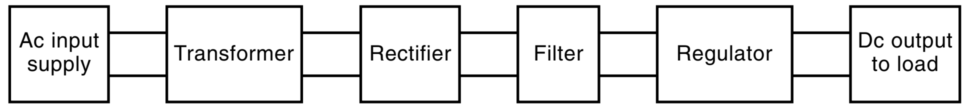


**Figure 2.** Block diagram showing components of power supply.

the diode. When not conducting, the diode has to withstand this peak inverse voltage (PIV) offered by the negative half cycle. In this case, the magnitude of PIV [also called *peak reverse voltage* (PRV)] equals $V_m$. The output waveform extends to $2\pi$ radians; however, only one half of the sine wave from 0 to $\pi$ is available across the load resistor. Expressed mathematically, this means

$$I_{dc} = (1/2\pi)\int_0^{\pi} I_m \sin\omega t\, dt = I_m/\pi$$

The integration is carried out from 0 to $\pi$ because the current between $\pi$ and $2\pi$ is zero. Across the output load resistance the dc voltage $V_{dc} = I_{dc}R = I_mR/\pi$.

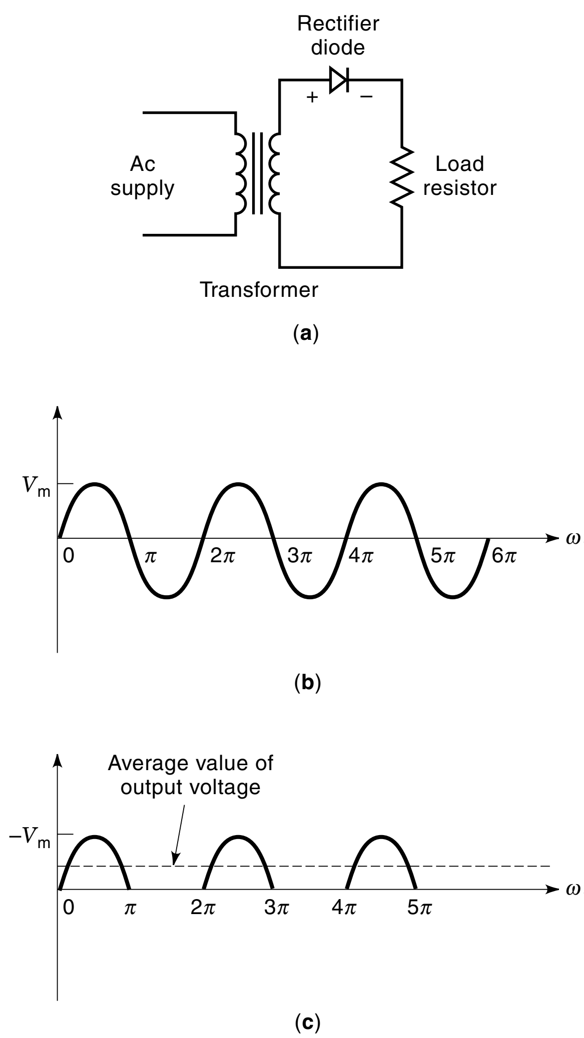


**Figure 3.** (a) Half-wave rectifier circuit; (b) input waveform shows both halves of sine wave; (c) output waveform across the load resistor shows only positive half cycle and negative half cycle appears across diode.

Similarly the dc voltage across the diode can be calculated mathematically. However, a simpler way is to apply Kirchhoffs voltage law. Since the sum of dc voltages should total zero, it is easily observed that the dc voltage across the diode $V_{diode} = -I_mR/\pi$ and the rms value of the current $I_{rms} = I_m/2$.

## FULL-WAVE RECTIFIER CIRCUIT

The full-wave rectifier circuit can be visualized as comprising two half-wave rectifier circuits, strategically connected to the center top of a transformer secondary coil. Such a circuit is shown in Fig. 4(a). Two semiconductor diodes are connected to the two ends of the transformer secondary coil. The load resistor is connected between the center tap of the transformer secondary coil and the junction of the negative electrodes of the two diodes. The primary coil of the transformer receives the ac input supply. The output voltage of the transformer secondary coil is again represented as $v_i = V_m \sin \omega t$. Here $V_m$ represents the peak transformer secondary coil voltage from one end to the center tap. Furthermore, let us again assume that the forward voltage drop of the diode is very small (this is normally represented as $V_\gamma$) compared to the input signal from the center-tapped transformer secondary coil. We have the relations $i_1 = i_{d1}$ and $i_2 = i_{d2}$, where $i_1$ is the current in one half of the transformer secondary coil circuit, $i_2$ is and the current in the other half of the transformer secondary coil circuit, and $i_{d1}$ and $i_{d2}$ are diode currents. Also, $i_R = i_1 + i_2$, where $i_R$ is the current in the resistance. The dc current can be calculated as in the previous case:

$$I_{dc} = 2I_m/\pi$$
$$V_{dc} = 2I_{mR}/\pi$$

where $I_m = V_m/R_f + R$).

It must, however, be remembered that in this case, $V_m$ represents the peak transformer secondary coil voltage from the center tap to one end of the transformer. (The half-wave rectifier did not utilize a center-tapped secondary coil.) Figure 4(b) represents the input waveform. Figure 4(c) through 4(h) represent the output waveforms. It is observed that the load resistance procures both halves of the sine wave. The output waveforms are always positive, regardless of the fact that the input waveform alternates between positive and negative states every half-cycle. This is because when the top end of the transformer secondary coil is positive with respect to the center tap, diode D1 conducts and permits the flow of current from right to left in the load resistor $R$. Diode D2 is "open" or "off" because the bottom end of the transformer secondary coil must be negative with respect to the center tap. When the bottom end of the transformer secondary coil is driven positive with respect to the center tap, diode D2 conducts and again permits the flow of current from right to left in the load resistor $R$. Diode D1 is open or off because the top-end of the transformer secondary coil must be negative with respect to the center tap. It can be seen that in this full-wave rectifier

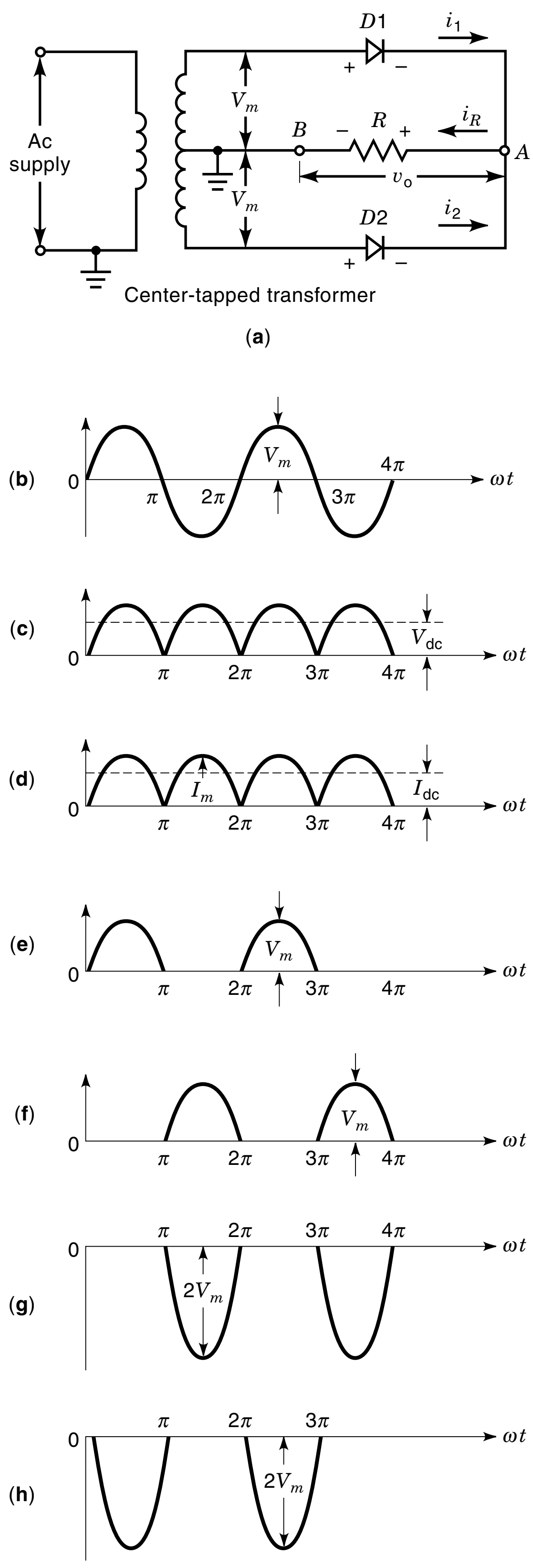


**Figure 4.** (a) Full-wave rectifier circuit (ideal diodes); (b) input waveform; (c) load voltage waveform; (d) load current waveform; (e) current in diode *D*1; (f) current in diode *D*2; (g) voltage across diode *D*1; (h) voltage across diode *D*2.

circuit, the PIV across *each* diode is *twice* the maximum transformer voltage measured from the center tap to either the top or bottom end. Voltages experienced by diodes D1 and D2 are shown in Figs. 4(g) and 4(h). In each case the voltages equal $2V_m$, where $V_m$ is the peak voltage corresponding to one half of the secondary coil.

## FULL-WAVE BRIDGE RECTIFIER CIRCUIT

When a center-tapped transformer is not available, a bridge rectifier circuit provides full-wave rectification. The bridge consists of four diodes connected in a systematic loop as shown in Fig. 5(a). This creates four junction points, *a*, *b*, *c*, and *d*, as shown in the diagram. The transformer secondary coil is connected between *b* and *c*, whereas the load resistor is connected between *a* and *d*, as shown. Figure 5(b) represents the top end of the transformer secondary coil being positive with respect to the bottom end. Only diodes D1 and D4 are capable of conducting. Diodes D2 and D3 are off. The transformer secondary coil, diode D1, the load resistor *R*, and the diode D4 all form a series circuit, permitting the current to flow in the load resistor from left to right. During the next half cycle, the top end of the transformer secondary coil is negative with respect to the bottom end. Therefore, only diodes D2 and D3 are capable of conducting. Diodes D1 and D4 are off. The transformer secondary coil, diode D2, the load resistor *R*, and the diode D3 form a series circuit, permitting the current to flow in the load resistor, again, from left to right. This is shown in Fig. 5(c). It is important to observe that the current in the load resistor is always from *a* to *d* regardless of whether *b* is positive or negative. The bridge rectifier circuit is the best choice; however, it suffers from a minor disadvantage. It needs four diodes instead of two. However, the PIV of each diode is only $V_m$ and not $2V_m$, as in the case of full-wave rectifier. Currently, ready-made bridges are mass manufactured and are available in an "encapsulated" form. A schematic is shown Fig. 5(d).

## VOLTAGE REGULATION

Voltage regulation provides the engineer a measure to study the behavior of the circuit under changing load-current conditions. The percentage of voltage regulation is defined as

$$\text{VR\%} = [100(V_{\text{no load}} - V_{\text{full load}})]/V_{\text{full load}}$$

Ideally, the voltage regulation of a well-designed power supply should be zero. In other words, the voltage delivered by the power supply should be totally independent of the current drawn by the load. Suppose the supply is rated 12 V dc. The instrument should deliver 12 V, whether it is delivering zero load current (no load) or 600 A load current. Such stringent specification require highly sophisticated electronic circuits. It is possible to achieve VR% of less than 1%. An example of a regulation curve is shown in Fig. 6. This graph indicates that the power-supply voltage drops from 12 V at zero current to 8 V at full load of 5 A. The percentage of voltage regulation can be calculated as follows:

$$\text{VR\%} = [(12 - 8)/8](100) = 50\%$$

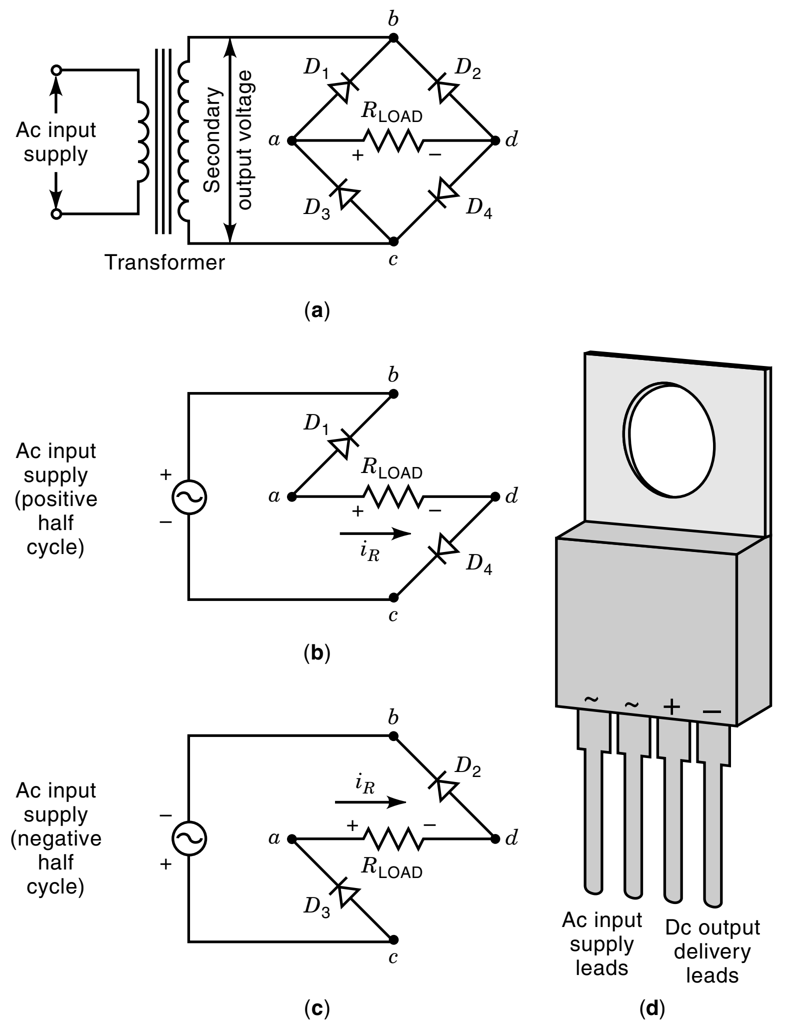


**Figure 5.** (a) Bridge rectifier circuit; (b) current path, top end positive; (c) current path, top end negative (observe that the current $i_R$ in the load resistance is always from $a$ to $d$, left to right); (d) encapsulated bridge rectifier.

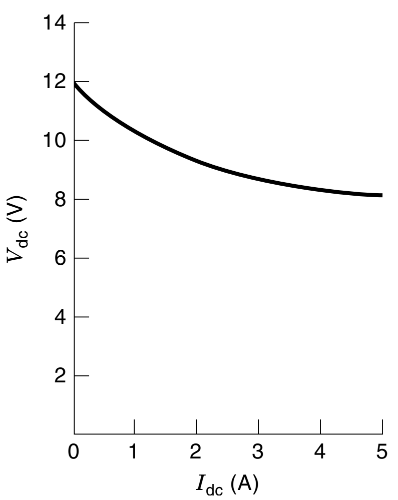


**Figure 6.** Regulation graph of a 12-V supply.

The minimum load resistance that can be connected to the power supply is calculated as

$$R_{\text{load (minimum)}} = V_{\text{full load}}/I_{\text{full load}} = 8/5 = 1.6\,\Omega$$

## RIPPLE

The output signal of a full-wave rectifier has a frequency equal to twice the value of the input signal frequency. With a 60 Hz input, a 120 Hz unwanted signal appears at the output, in addition to the dc output. This undesired ac component of output is called *ripple.* In other words, ripple is small amounts of alternating current waveforms superimposed on the dc waveform. The ratio of the amount of ripple to the dc value is called the *ripple factor.* It can also be expressed in percent values and identified as *percent ripple.* The ripple factor provides the engineer with a measure to examine the effectiveness of the rectifier circuit. A ripple factor greater than 1 means that the amount of alternating current in the output is greater than the amount of direct current in the output. It is imperative that rectifier circuits need to be appropriately designed to achieve ripple factors less than 1. The engineer

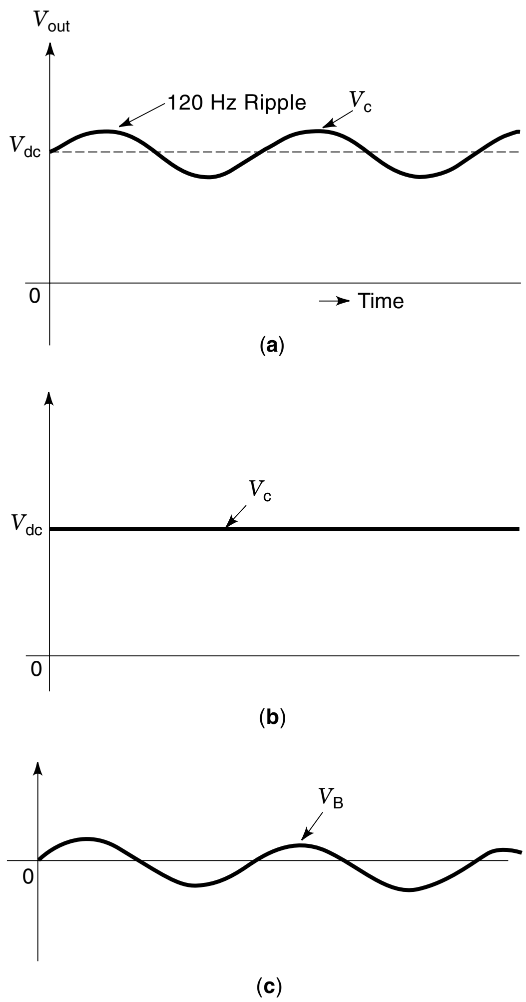


**Figure 7.** (a) Output waveform of a power supply unit contains a 120 Hz ripple; (b) dc component of the output waveform; (c) ac component of the output waveform.

can thus ensure that the amount of alternating current in the output is less than the amount of direct current in the output. Ripple is directly proportional to the load current $I_{dc}$ and inversely proportional to the capacitance. However, capacitive filters help provide "smooth" dc output waveforms. Let Fig. 7(a) represent the output waveform of a power-supply unit. This waveform is made up of two components, a dc component shown in Fig. 7(b), and an ac component, shown in Fig. 7(c). A perfectly designed rectifier circuit should deliver a smooth dc output.

Mathematically, we can write this statement as

$$V_a^2 + V_b^2 = V_c^2$$

Ripple has been defined as the ratio of $V_b$ to $V_a$, $V_b/V_a$. If the rms value of the ripple voltage is given as $V_r$, then the ripple factor is $V_r/V_{dc}$.

## FILTERS

The pulsating dc output signals from the half-wave, full-wave, and bridge rectifiers have very limited applications. Almost all electronic circuitry demands a *smooth* dc voltage that is constant in value and closely resembles the output voltage of a good battery source. This conversion of half-wave and full-wave signals to constant dc voltage values is accomplished using a filter. Several types of filters are available, the simplest being a single capacitor. Other types include a *choke filter, π filter,* and *double π filter.* The capacitor charges when the diode is conducting and discharges via the load resistor when the diode is off. The action of the capacitor can be examined by referring to Figs. 8(a) to 8(e). Let us choose a large capacitor so that the capacitance sustains a voltage as defined by the point *a* or *c* as shown in Fig. 8(b). During the positive

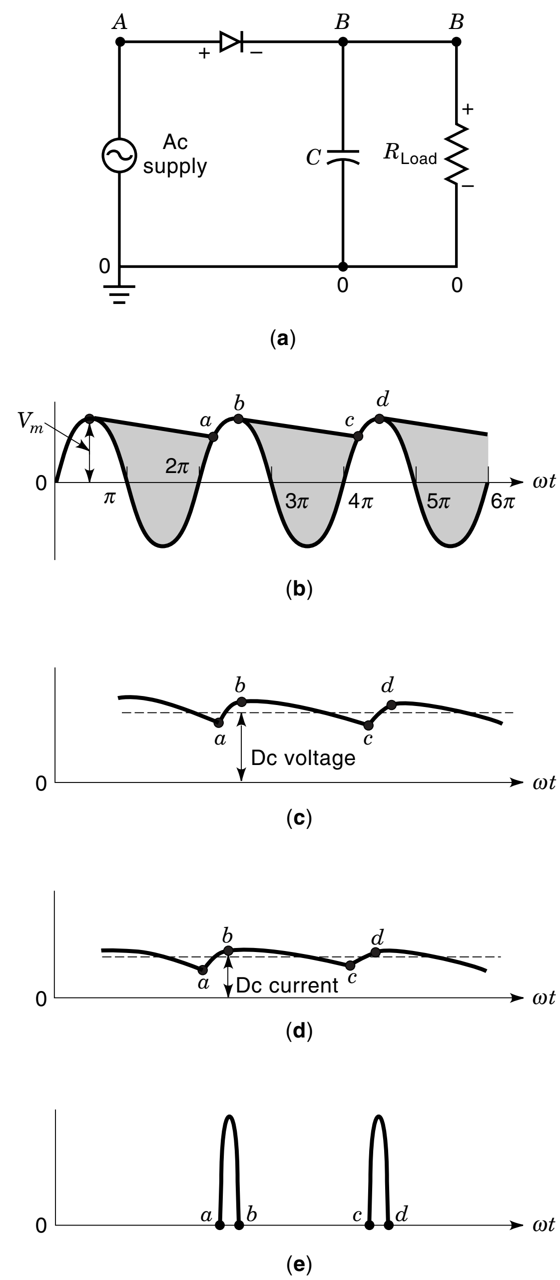


**Figure 8.** (a) Half-wave rectifier with a capacitor filter across the load resistor; (b) capacitor must be large enough to "fill" in the "valleys" (shaded); (c) voltage across load resistor; (d) current through load resistor; (e) diode current.

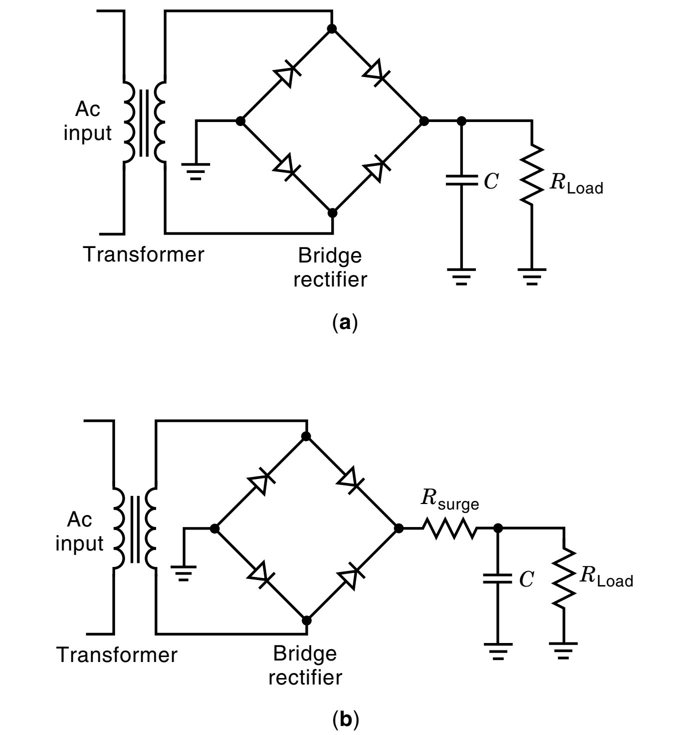


**Figure 9.** (a) Bridge rectifier with load resistor $R_{\text{LOAD}}$ and filter capacitor $C$; (b) the addition of a surge resistance limits the sudden gush of current that takes place during the instant the circuit is energized.

half of the supply cycle, when the diode is conducting, the capacitor gets charged. This charging operation takes place during the time interval between $a$ and $b$. At point $b$ the charging current ceases because the diode is reverse biased and has stopped conducting. But the load continues to receive current from the discharging capacitor during the time interval from $b$ to $c$. Again, at point $c$ the capacitor begins its charging operation and the cycle repeats. The load resistor voltage and current waveforms are shown in Figs. 8(c) and 8(d), respectively. A full-wave rectifier with a single capacitance across the load is shown in Fig. 8(e). The corresponding output waveform, with the action of its filter capacitor, is shown in Fig. 8(f). An approximate analysis yields

$$V_{\text{dc}} = V_{\text{m}} - I_{\text{dc}}/4fC$$

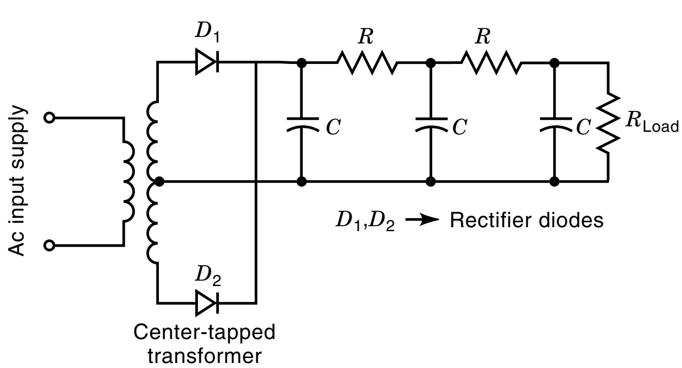


**Figure 10.** Two-section $R$–$C$ filter can reduce the ripple by a factor of $\alpha^2$ where $\alpha$ is the ripple factor for one $R$–$C$ section.

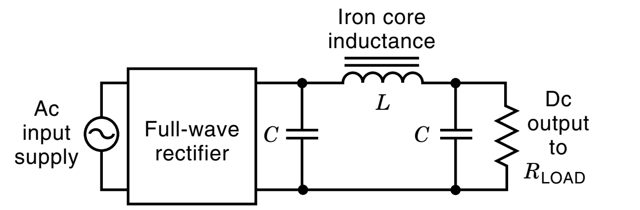


**Figure 11.** Full-wave rectifier with $\pi$ filter ($L$–$C$ combination) and load resistor $R$.

where $f$ is the power line frequency and $C$ represents the value of filter capacitor used.

Instead of using only a capacitance, sometimes a resistance called the *surge resistance* is often used in addition to the load resistance, as shown in Fig. 9(b). The filter capacitor is initially uncharged and acts as a "short circuit" when the circuit shown in Fig. 9(a) is energized. Therefore there is sudden *inrush* of current, and this is called the *surge current.* In some cases this current surge may be large enough to destroy the diodes. Therefore a current-limiting resistor is added in series as shown in Fig. 9(b). Other combinations of resistances and capacitances are also used. A two-section $R$–$C$ filter used in conjunction with a full-wave rectifier is shown in Fig. 10.

When the load current is heavy, an $L$–$C$ filter, which is also called a *choke filter,* is preferred to an $R$–$C$ filter. The ripple can be reduced by choosing the inductive reactance to be much higher than the capacitive reactance. For example, if $X_L$ is ten times as large as $X_C$, then the ripple is attenuated by a factor of 10. An example wherein a full-wave rectifier employs one section in which $L$–$C$ filters are used is shown in Fig. 11. This is also called a $\pi$ filter. Using two sections results in an improvement in the value of ripple. Still further reduction in ripple can be accomplished by using a double $\pi$ filter as shown in Fig. 12. However, the voltage regulation may be poorer because of voltage drop in the choke filters. Rectifier circuits combined with appropriate filter circuits provide a convenient method of converting ac to dc. However, the proper choice depends upon the application desired. Some of the factors that need to be considered are the permissible ripple, the regulation required, the nature of load current desired, the size and weight of the complete network, and the cost of components. A choke filter should consist of pure inductance; however, it possesses a small amount of resistance. A $\pi$ filter that includes the choke resistance of the coil as well

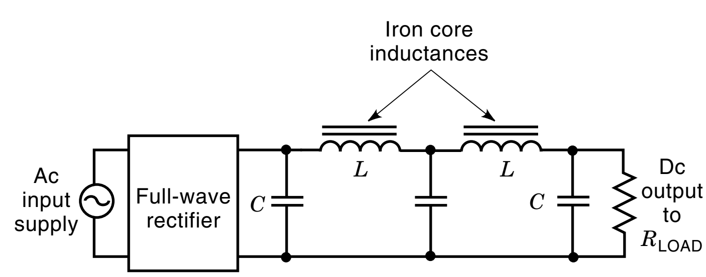


**Figure 12.** Full-wave rectifier with double $\pi$ filter.

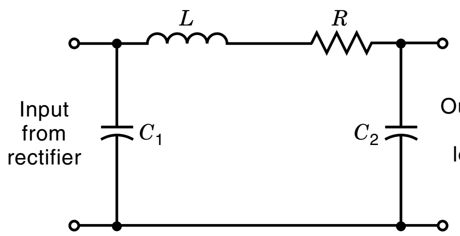


**Figure 13.** Capacitance input $\pi$ filter.

is shown in Fig. 13. This is also called a capacitance input filter. Another version, called a "Tee" filter or a choke input filter is shown in Fig. 14. Under light load conditions, capacitor input filters help rectifiers generate fairly smooth dc signals with small ripple. However, the regulation is relatively poor. In addition, as the load currents increase ripple also increases.

## RATIO OF RECTIFICATION

The *ratio of rectification* is defined as the ratio of dc output power delivered by the rectifier circuit to the ac input power delivered to the rectifier circuit. It needs to be recognized that the transformer is an ac apparatus and therefore it is possible to calculate the rms value of the load voltage and the rms value of the load current. The product of these two values yields the total power delivered by the transformer. However, the objective of the rectifier circuit is to provide direct current to the load. Therefore one can calculate the dc voltage and the dc current at the load resistor. The product of these two quantities results in the dc load power. The ratio of rectification can thus be determined. However, this ratio should not be confused as an efficiency measure because efficiency calculations include the losses in the transformer as well as the diodes.

### Voltage Doublers

By suitably modifying the full-wave and the bridge rectifier circuits, it is possible to create circuits that can provide twice the peak supply voltage, or $2V_m$. By cascading several voltage doubler circuits suitably, it is possible to generate very high dc voltages. The full-wave voltage doubler circuit is shown in Fig. 13(a). Another interpretation of the circuit is shown in Fig. 13(b) wherein the load resistor is omitted for sake of clarity. Diode D1 charges the capacitor C1 when the top end of the supply source is positive with respect to the bottom end. Similarly, diode D2 charges the capacitor C2 when the bottom end is positive with respect to the top end of the input source. In this circuit, each capacitor is charged once per cycle, but at different times. The capacitors therefore receive two charging pulses per cycle. Furthermore it is observed that capacitances C1 and C2 are in series. This results in a doubling effect. Figure 13(c) shows the waveform across the two capacitors and indicates how they add up. The load resistor may be connected between the two extreme ends of the two capacitors as shown in the diagram. The ripple frequency is twice the frequency of the supply and the ripple is greater and the regulation poorer compared with an equivalent full wave rectifier.

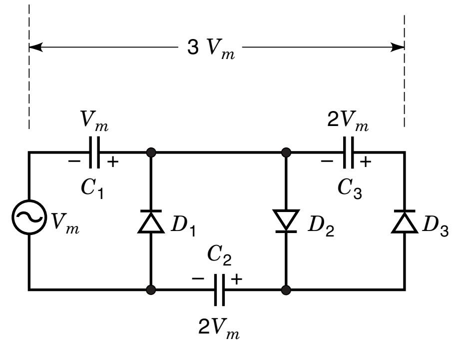


**Figure 15.** Voltage tripler.

Figure 14(a) shows the half-wave voltage doubler circuit. It is also called the cascade voltage doubler circuit. Diode D1 operates when the bottom end of the supply is positive and charges the capacitor C1 to the maximum value of the supply voltage $V_m$ as shown. During the next half cycle, when the top end of the supply is positive, the supply voltage is actually "aiding" the capacitor C1 because of the series connection of the supply and capacitor C1. The maximum possible value is $2V_m$, and therefore the capacitor C2 charges to the same value of $2V_m$ via diode D2. The load need only be connected across capacitor C2, unlike the previous case wherein the load was connected across a series combination of capacitors C1 and C2. Therefore the load receives only one charging pulse per cycle. The ripple is very high, but its frequency in this case is the same as the supply line frequency. The voltage regulation of this circuit is also very poor.

Voltage tripler and voltage quadrupler circuits are shown in Figs. 15 and 16. It is possible to design circuits that provide more than $4V_m$. However, the such circuits result in extremely poor voltage regulation.

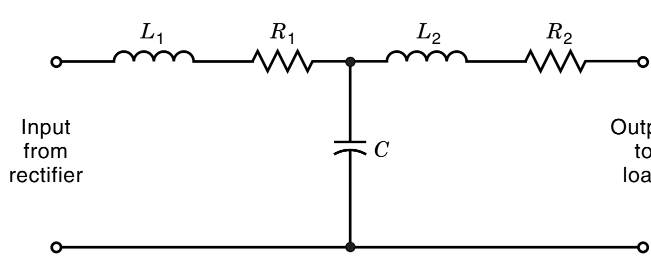


**Figure 14.** Choke input tee filter.

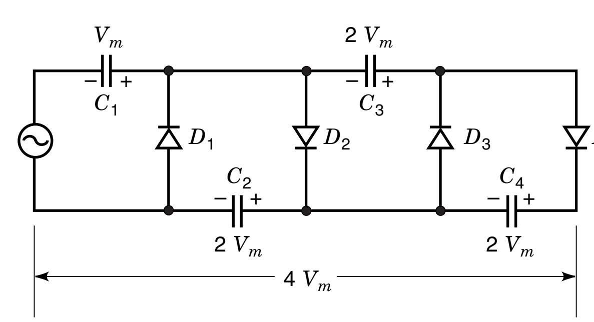


**Figure 16.** Voltage quadrupler.

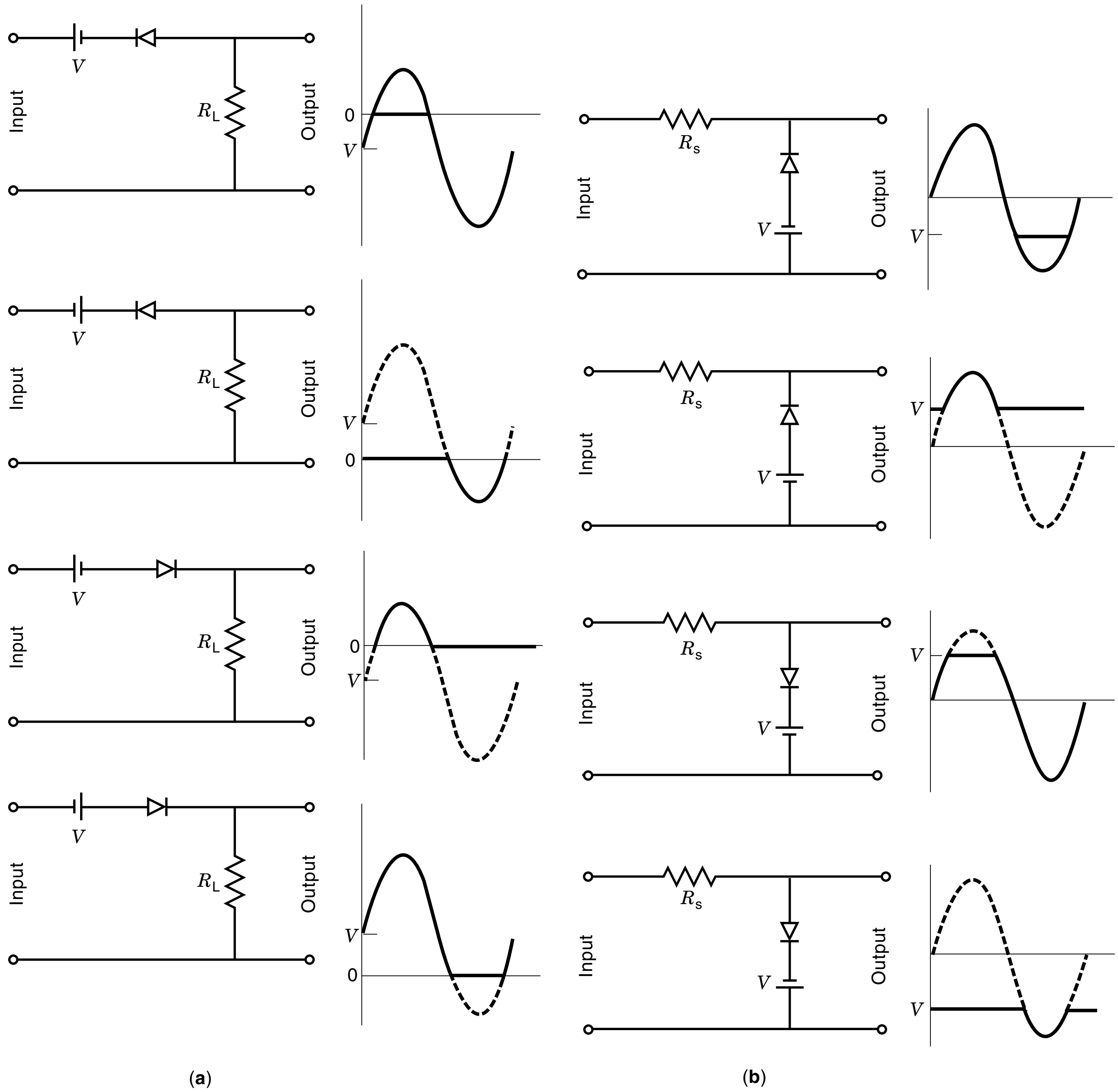


**Figure 17.** Clipper circuits modify the sine wave input. (Input voltage waveform remains the same for all circuits.) (a) Left: Rectifier diodes used as "clippers"; Right: Waveform across output load resistor $R_L$. (b) Left: Rectifier diodes used as "clippers"; Right: Waveform across, output, diode–battery series combination where $R_S$ = series resistor.

## Clippers

Many electronic circuits demand the removal of unwanted signals below or above a predetermined or specified voltage level. By suitably rearranging a diode rectifier circuit and a dc battery power supply, it is possible to obtain a variety of clipper circuits. A sample of selected *clipper circuits* along with their output waveforms is shown in Fig. 17. All these circuits assume a sinusoidal input voltage of 50 V peak-to-peak magnitude ($V_m$ = 25 V).

## Clampers

A clamper adds a dc component to the signal. The principle is to utilize the charging nature of a capacitor. Selected examples of clamper circuits are shown in Fig. 18. The clamper is also called a *dc restorer,* particularly when associated with television circuitry. All these circuits assume a sinusoidal input voltage of 50 V peak-to-peak magnitude ($V_m$ = 25 V).

## APPENDIX 1. HALF-WAVE RECTIFIER CALCULATIONS

The rms value of a complete sine wave is $V_m/\sqrt{2}$. The output of the half-wave rectifier is only one half of a sine wave. Therefore, the rms value of the load voltage is equal to $(1/\sqrt{2})(V_m/\sqrt{2}) = V_m/2$. The average or dc value $V_{dc}$ of this rectified sine wave is $V_{dc} = V_m/\pi = 0.318V_m$. The rms value of

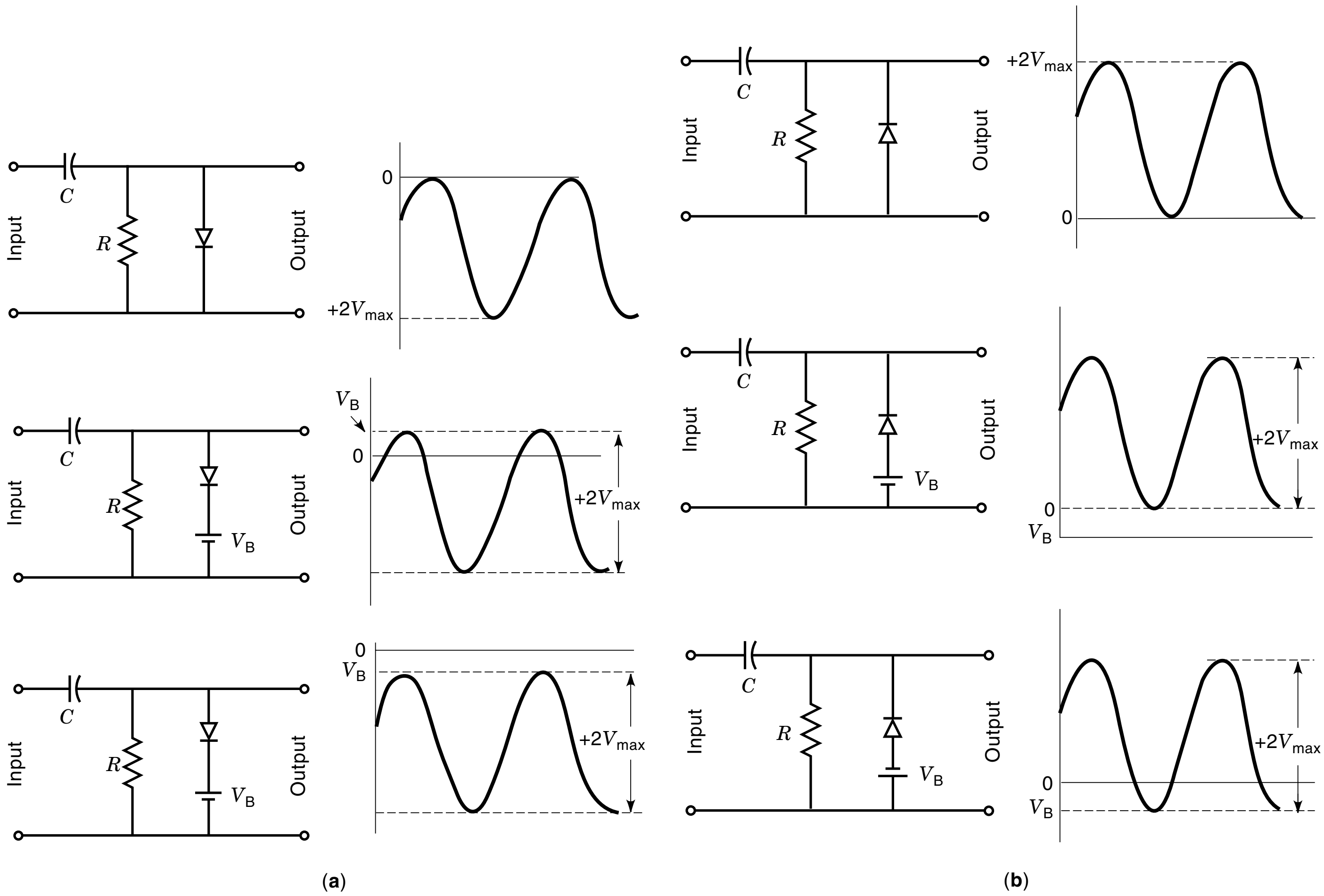


**Figure 18.** (a) Clamper circuits retain shape of the input sine waveform, but add a dc "bias" to the waveform. (b) Left: While designing clamping circuits, it is essential that 5 $RC \gg T/2$, where $T$ = period of sine wave; Right: Output waveforms of clamping circuits obtained across resistance, $R$ (Input voltage waveform for all six clamping circuits).

the ripple voltage is $V_r$. Therefore $(V_m/2)^2 = (V_m/\pi)^2 + (V_r)^2$ Solving, $V_r = 0.386V_m$.

The ripple factor is $V_r/V_{dc} = 0.386V_m/0.318V_m = 1.21$.

| | |
|---|---|
| ac load voltage | $V_m/2$ |
| ac load current | $(V_m/2)/R$ |
| ac load power | $(V_m/2)[(V_m/2)/R] = V_m^2/4R$ |
| dc load voltage | $V_m/\pi$ |
| dc load current | $V_m/\pi R$ |
| dc load power | $(V_m/\pi)(V_m/\pi R) = V_m^2/\pi^2 R$ |

The ratio of rectification is the dc load power divided by the ac load power, or $(V_m^2/\pi^2 R)/(V_m^2/4R)$. The ratio of rectification is $4/\pi^2 = 0.406$. *This is no indication of the efficiency;* however, it can be stated that the *overall operating efficiency* of a half-wave rectifier with a resistive load cannot be greater than 40.6%. An ideal rectifier has no losses and has therefore a 100% "power" efficiency.

The rating of the secondary winding of the transformer is $V_m/\sqrt{2}$ V.

| | |
|---|---|
| ac current in the secondary winding the ac load current | $(V_m/2)/R$ A |
| ac power rating of the transformer | $(V_m/\sqrt{2})[(V_m/2)/R] = V_m^2/2\sqrt{2}R$ W |
| Transformer utilization factor | (dc load power)/(ac power rating) |
| Transformer utilization factor | $(V_m^2/\pi^2 R)/(V_m^2/2\sqrt{2}R) = 2\sqrt{2}/\pi^2 = 0.287$ |

## APPENDIX 2: FULL-WAVE RECTIFIER CALCULATIONS

In this case both halves of the ac input sine wave are rectified and utilized. Therefore the magnitude of several of the values that were calculated for the half-wave rectifier gets multiplied by a factor of 2. The rms value of a complete sine wave is $V_m/\sqrt{2}$. The average of dc value of the rectified sine wave $V_{dc} = 2V_m/\pi = 0.636V_m$. The rms value of the ripple voltage is $V_r$. Therefore $(V_m/\sqrt{2})^2 = (2V_m/\pi)^2 + (V_r)^2$. Solving, $V_r = 0.307V_m$.

The ripple factor is $V_r/V_{dc} = 0.307V_m/0.636V_m = 0.482$.

| | |
|---|---|
| ac load voltage | $V_m/\sqrt{2}$ |
| ac load current | $(V_m/\sqrt{2})/R$ |
| ac load power | $(V_m/\sqrt{2})[(V_m/\sqrt{2})/R] = V_m^2/2R$ |
| dc load voltage | $2V_m/\pi$ |

**Table 2. Rectifier Circuit Terminology**

| Term | Input (ac) | Output (dc) |
|---|---|---|
| Half-wave rectifier[a] | $V_{RMS} = (V_m/\sqrt{2}) = 0.707V_m$<br>$I_{RMS} = (I_m/2) = 0.5I_m$ | $V_{dc} = V_{AVG} = (V_m/\pi) = 0.318V_m$<br>$I_{dc} = I_{AVG} = (I_m/\pi) = 0.318I_m$ |
| Efficiency of HWR (purely resistive load) | $[(I_{DC})^2R_{LOAD}]/[(I_{AC})^2R_{LOAD}] = (0.318I_m)^2/(0.5I_m)^2 = 0.406$ | |
| | $V_{RMS} = (V_m/\sqrt{2}) = 0.707V_m$<br>$I_{RMS} = (I_m/\sqrt{2}) = 0.707I_m$ | $V_{dc} = V_{AVG} = 2(V_m/\pi) = 0.636V_m$<br>$I_{dc} = I_{AVG} = 2(I_m/\pi) = 0.636I_m$ |
| Efficiency of FWR (purely resistive load) | $[(I_{dc})^2R_{LOAD}]/[(I_{AC})^2R_{LOAD}] = (0.636I_m)^2/(0.707I_m)^2 = 0.812$ | |

[a] It is important to observe that in a half-wave rectifier (HWR), the voltage is present during both half cycles. Therefore, $V_{RMS} = 0.707\ V_m$; however, the current flows for only one half cycle. Therefore $I_{RMS} = 0.5\ I_m$. For the above calculations, an ideal rectifier has been assumed and therefore the internal resistance of the rectifier $r_\gamma$ has been ignored.

dc load current $\quad 2V_m/\pi R$
dc load power $\quad (2V_m/\pi)(2V_m/\pi R) = 4V_m^2/\pi^2 R$

The ratio of rectification is the dc load power divided by the ac load power, or $(4V_m^2/\pi^2 R)/(V_m^2/2R)$. The ratio of rectification is $8/\pi^2 = 0.812$. The overall operating efficiency is therefore twice that of a half-wave rectifier, that is, 81.2%.

The full-wave rectifier utilizes the center-tapped secondary winding of a transformer. But the primary coil has a single winding. Therefore the calculations for the primary and secondary circuits must be done separately. The secondary coil of the transformer actually contains *two* circuits. *Each* circuit performs the function of a half-wave rectifier. Therefore the transformer utilization factor for the secondary coil is twice that of the half-wave rectifier.

The transformer utilization factor for secondary winding is $2(0.287) = 0.574$. Disregarding the center tap, we can calculate the transformer utilization factor for the primary winding.

dc load voltage $\quad V_{dc} = 2V_m/\pi$
dc load current $\quad I_{dc} = 2V_m/\pi R = 2I_m/\pi,\ I_m = V_m/R.$

The rating of the transformer winding can be calculated using the rms values of voltage and current:

$$V_{rms} = V_m/\sqrt{2}\,\mathrm{V}, I_{rms} = I_m/\sqrt{2}\,\mathrm{A}$$

Substituting and rearranging, we obtain

$$V_{dc} = (2\sqrt{2}/\pi)V_{rms}$$
$$I_{dc} = (2\sqrt{2}/\pi)I_{rms}$$

The dc power can now be determined in terms of the ac power:

$$V_{dc}I_{dc} = (8/\pi^2)V_{rms}I_{rms}$$

The transformer utilization factor is the dc power divided by the ac power or $V_{dc}I_{dc}/V_{rms}I_{rms} = 8/\pi^2 = 0.812$. The average transformer utilization factor is $(0.574 + 0.812)/2 = 0.693$.

## APPENDIX 3. BRIDGE RECTIFIER RIPPLE CALCULATIONS

Both halves of the ac input sine wave are rectified and utilized in a bridge rectifier as well. Therefore many of the calculations that were carried out for the full-wave rectifier are still valid in this case. The rms value of a complete sine wave is $V_m/\sqrt{2}$. The average or dc value of the rectified sine wave $V_{dc} = 2V_m/\pi = 0.636V_m$. The rms value of the ripple voltage is $V_r$. Therefore $(V_m/\sqrt{2})^2 = (2V_m/\pi)^2 + (V_r)^2$. Solving, $V_r =$

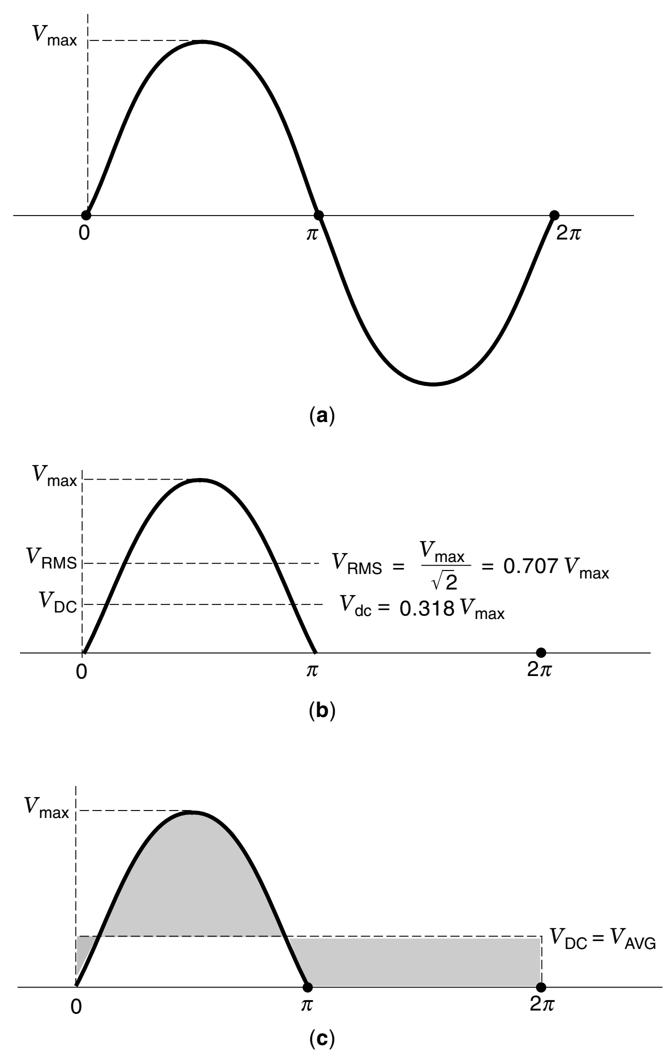


**Figure 19.** Half-wave rectification waveforms: (a) One full cycle of input sine wave; (b) Output waveform: half-wave rectifier; (c) Averaging over one full cycle.

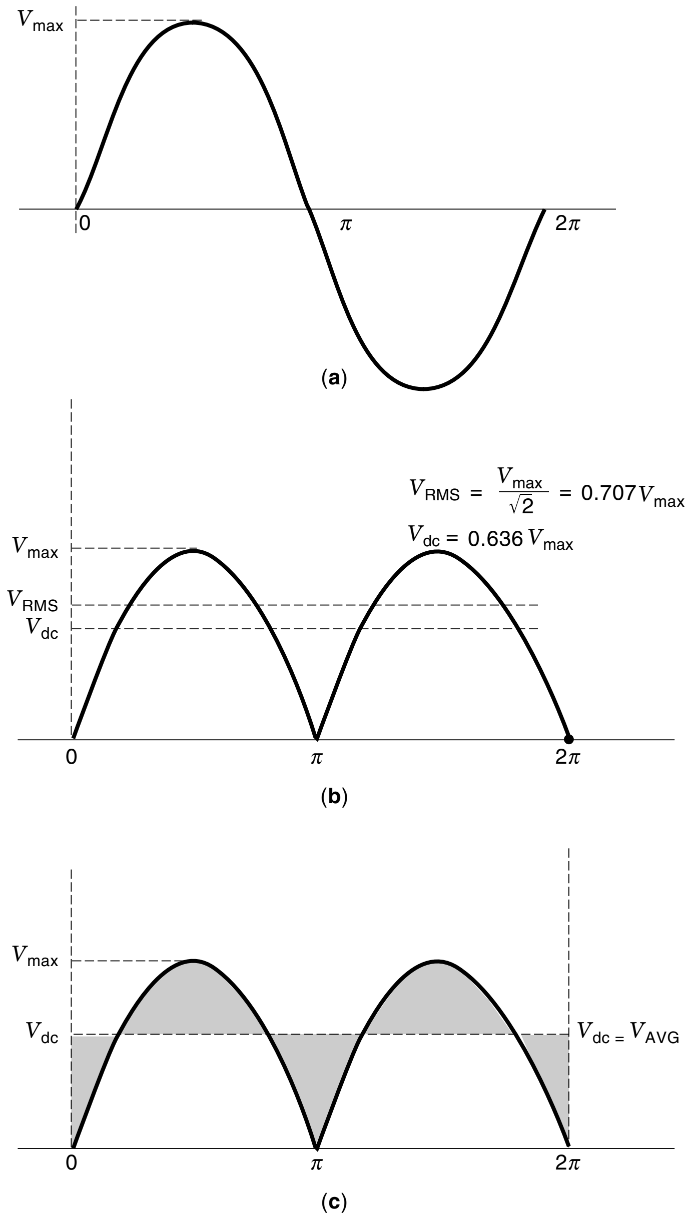


**Figure 20.** Full-wave rectification waveforms: (a) One full cycle of input sine wave; (b) Output waveform: full-wave rectifier; (c) Averaging over one full cycle.

$0.307V_m$. The ripple factor is $V_r/V_{dc} = 0.307V_m/0.636V_m = 0.482$. The ratio of rectification will not change and remains 0.812, as it was for the full-wave rectifier. There is no secondary center tap; therefore the transformer utilization factor is 0.812, as it was for the full-wave rectifier when we disregarded the center tap.

## EPILOGUE

The main objective of a rectifier circuit is to convert alternating current/voltage into pure direct current/voltage. A rectifier diode accomplishes this. As an example, 1N4004 diode has a rating of 1 ampere and 400 volts PIV. However, instead of providing a *steady* output current/voltage, the rectifier circuit might be delivering a current/voltage that may have considerable variation, or *ripple* in the rectified output. A *ripple factor* is therefore defined, that helps in evaluating and comparing different rectifier circuits.

$$\text{Ripple factor} = \frac{\begin{array}{c}\text{Effective value of alternating current}\\ \text{portion of rectified output wave}\end{array}}{\text{Average value of rectified output wave}}$$

A *filter* is a circuit that is used to eliminate undesired ripple from the output voltage of the rectifier. Normally, a well-designed capacitor is used to obtain a smooth dc output from a rectifier. The necessary capacitance can be calculated using the following formula:

$$C = [(\text{load current})(\text{one full cycle of waveform})]/[\text{twice ripple voltage}]$$

For example, using the frequency in the U.S., i.e., 60 Hz, period = 1/60 s. If the load current is 10 amperes and only 3 volts peak-to-peak ripple voltage is permitted, then capacitance required will be [10(1/60)]/[(2)(3)] =27,777.77 microfarads.

Table 2 and Figs. 19 and 20 help clarify the terminology associated with rectifier circuits.

## BIBLIOGRAPHY


C. L. Alley and K. W. Atwood, *Microelectronics,* Englewood Cliffs, NJ: Prentice-Hall, 1986.

G. L. Batten, Jr., *Programmable Controllers,* New York: McGraw-Hill, 1994.

D. A. Bell, *Electronic Devices and Circuits,* 3rd ed., Englewood Cliffs, NJ: Prentice-Hall, 1980.

R. Boylestad and L. Nashelsky, *Electronic Devices and Circuit Theory,* 3rd ed., Englewood Cliffs, NJ: Prentice-Hall, 1982.

J. J. Carr, *Elements of Electronic Instrumentation and Measurement,* 3rd ed., Englewood Cliffs, NJ: Prentice-Hall, 1996.

J. J. Carr, *Sensors and Circuits,* Englewood Cliffs, NJ: Prentice-Hall, 1993.

J. R. Carstens, *Electrical Sensors and Transducers,* Prentice-Hall, 1993.

G. M. Chute and R. D. Chute, *Electronics in Industry,* 5th ed., New York: McGraw-Hill, 1979.

W. D. Cooper and A. D. Helfrick, *Electronic Instrumentation and Measurement Techniques,* Englewood Cliffs, NJ: Prentice-Hall, 1985.

E. O. Doebelin, *Measurement Systems,* 4th ed., New York: McGraw-Hill, 1990.

E. O. Doebelin, *Engineering Experimentation,* New York: McGraw-Hill, 1995.

R. C. Dorf and J. A. Svoboda, *Introduction to Electric Circuits,* 3rd ed., New York: Wiley, 1996.

R. C. Dorf and R. H. Bishop, *Modern Control Systems,* 7th ed., Reading, MA: Addison-Wesley, 1995.

J. R. Eaton and E. Cohen, *Electric Power Transmission Systems,* 2nd ed., Englewood Cliffs, NJ: Prentice-Hall, 1983.

D. G. Fink and H. W. Beaty, *Standard Handbook for Electrical Engineers,* New York: McGraw-Hill, 1993.

A. R. Hambley, *Electronics,* New York: Macmillan, 1994.

M. Kaufman and A. H. Seidman, *Handbook of Electronics Calculations,* New York: McGraw-Hill, 1979.

E. N. Lurch, *Fundamentals of Electronics,* 3rd ed., New York: Wiley, 1981.

A. P. Malvino, *Electronic Principles,* 2nd ed., New York: McGraw-Hill, 1979.

J. Millman and A. Grabel, *Microelectronics,* 2nd ed., New York: McGraw-Hill, 1987.

M. H. Rashid, *Microelectronic Circuits,* Boston, MA: PWS Publishing Co., 1999.

J. Webb and K. Greshock, *Industrial Control Electronics,* Columbus, Ohio: Merrill Publishing Co., 1990.

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