UNIT-1

1.1 Electronics Circuits:

1.1.1 Power supplies- Block diagram

The block diagram of a d.c. power supply is shown in Fig. 1.1.

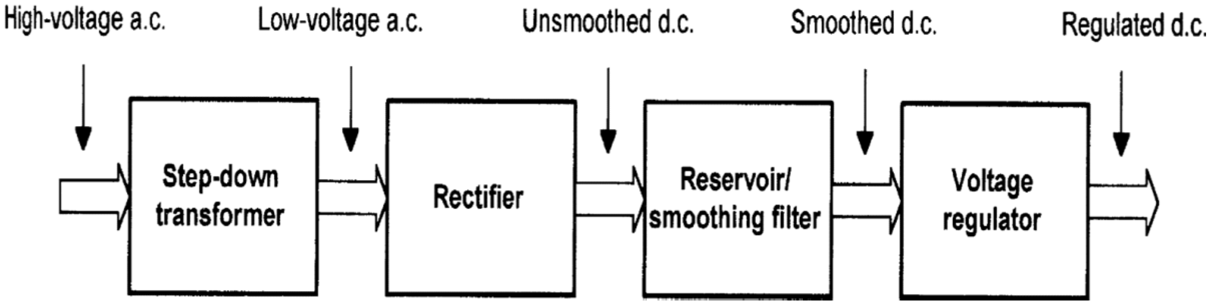


Figure 6.1 Block diagram of a d.c. power supply

- The mains input is at a relatively high voltage; a step-down transformer of appropriate turns ratio is used to convert this to a low voltage.
- The a.c. output from the transformer secondary is then rectified using conventional silicon rectifier diodes to produce an unsmoothed (or pulsating d.c.) output.
- This is then smoothed and filtered before being applied to a circuit which will regulate (or stabilize) the output voltage so that it remains relatively constant in spite of variations in both load current and incoming mains voltage.
- Fig. 1.2 shows the realization of the block diagram of a d.c. power supply using the electronic components in Fig. 1.1.

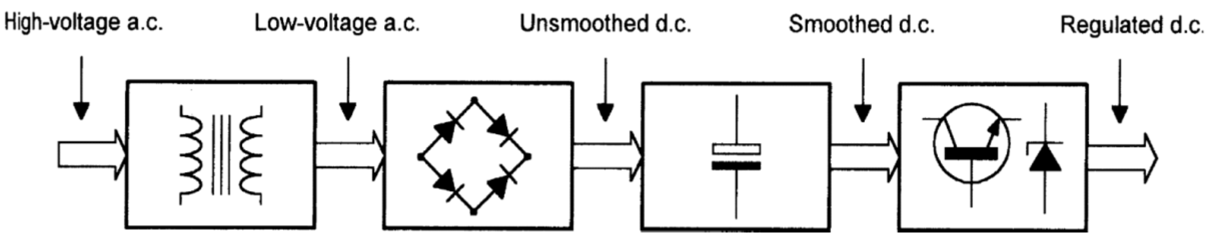


Figure 1.2 Block diagram of a d.c. power supply showing principal components

- The iron-cored step-down transformer feeds a rectifier arrangement.

- The output of the rectifier is then applied to a high-value reservoir capacitor. This capacitor stores a considerable amount of charge and is being constantly topped-up by the rectifier arrangement. The capacitor also helps to smooth out the voltage pulses produced by the rectifier.
- Finally, a stabilizing circuit (often based on a series transistor regulator and a Zener diode voltage reference) provides a constant output voltage.

1.1.2 Rectifiers:

- Rectifiers are the circuits which converts a.c voltage to pulsating d.c voltage.
- Rectifiers can be grouped into two types:
  i) Half-wave Rectifier
  ii) Full-wave Rectifier

i) Half-wave Rectifier

- The simplest form of rectifier circuit makes use of a single diode and, since it operates on only either positive or negative half-cycles of the supply, it is known as a half-wave rectifier. Fig. 1.3 shows a simple half-wave rectifier circuit.

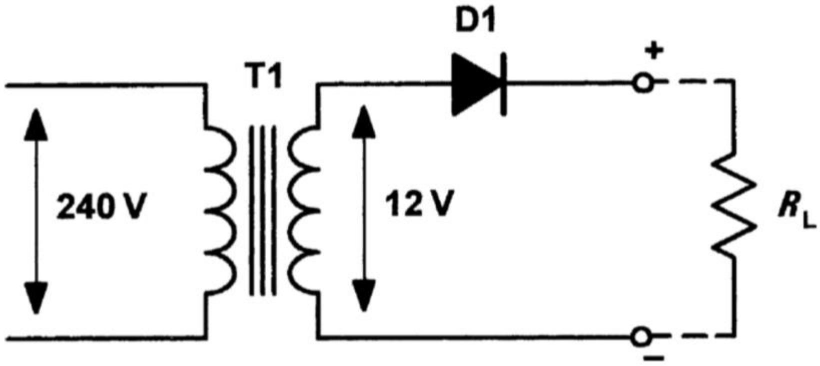


Figure 1.3 A simple half-wave rectifier circuit

- The mains voltage (220 to 240 V) is applied to the primary of a step-down transformer (T1).
- The secondary of T1 steps down the 240 V r.m.s. to 12 V r.m.s.
- Diode D1 will only allow the current to flow in the direction shown (i.e. from cathode to anode). D1 will be forward biased during each positive

half-cycle and will effectively behave like a closed switch as shown in Fig. 1.4.

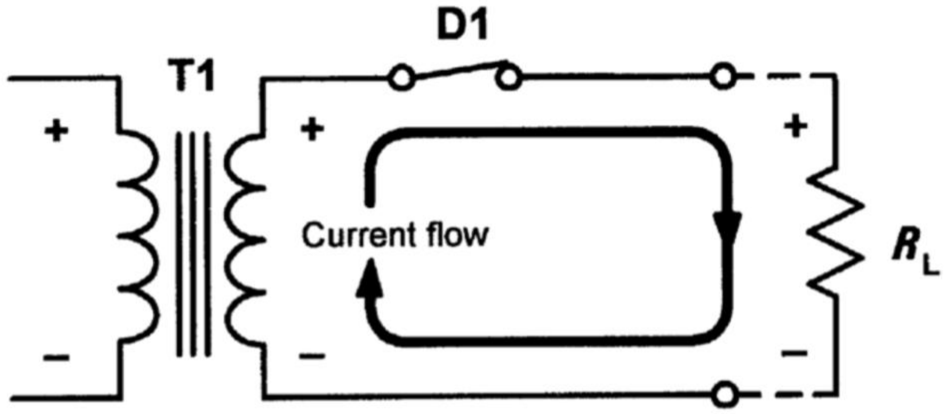


Figure 1.4 Half-wave rectifier circuit with D1 conducting (positive-going half-cycles of secondary voltage)

- When the circuit current tries to flow in the opposite direction, the voltage bias across the diode will be reversed, causing the diode to act like an open switch as shown in Fig. 1.5.

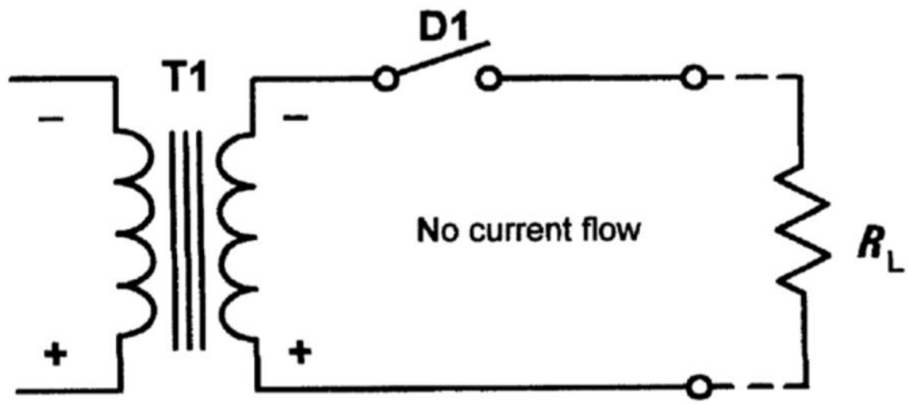


Figure 1.5 half-wave rectifier with D1 not conducting (negative-going half-cycles of secondary voltage)

- During positive half cycle, the diode D1 is forward biased, thus the current flows through the load R_L and voltage is developed across it.
- During negative half cycle, the diode D1 is reverse biased, thus there will be no flow of current through the load R_L, thereby the output voltage is zero.
- The input and output voltage waveform of a half-wave rectifier is shown in Fig. 1.6.

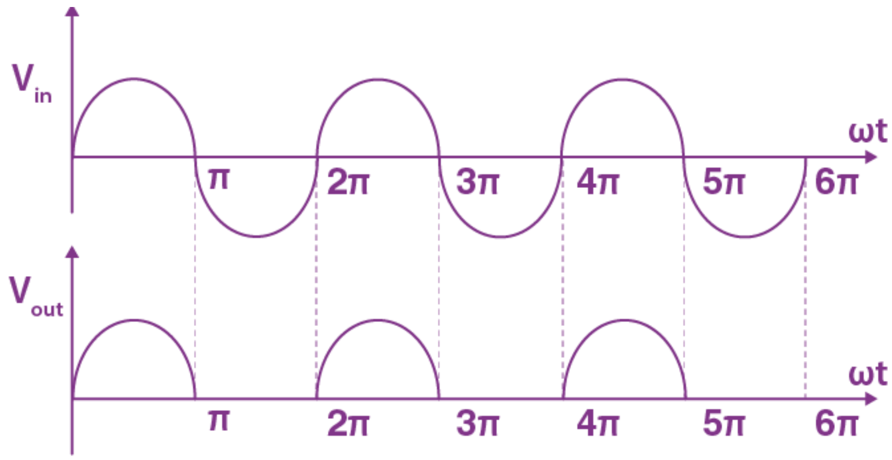


Figure 1.6 The input and output voltage waveform of a half-wave rectifier

- The relation between turns ratio and voltage of the primary and secondary of the transformer is given by:

$$\frac{N_1}{N_2} = \frac{V_{p(rms)}}{V_{s(rms)}}$$

- The peak voltage output from the transformer's secondary winding will be given by:

$$V_{pk} = 1.414\, V_{s(rms)}$$

Example 1.1

A mains transformer having a turns ratio of 44:1 is connected to a 220 V r.m.s. mains supply. If the secondary output is applied to a half-wave rectifier, determine the peak voltage that will appear across a load.

Solution

Given: $N_1 = 44$; $N_2 = 1$; $V_{p(rms)} = 220V$; $V_{s(rms)} = ?$

The r.m.s. secondary voltage will be given by:

$$\frac{N_1}{N_2} = \frac{V_{p(rms)}}{V_{s(rms)}}$$

$$V_{s(rms)} = \frac{V_{p(rms)}\ X\ N_2}{N_1} = \frac{220\ X\ 1}{44} = 5\text{V}.$$

The peak voltage developed after rectification will be given by:

V_{pk}= 1.414 X $V_{s(rms)}$ = 1.414 X 5V = 7.07 V.

Assuming that the diode is a silicon device with a forward voltage drop of V_γ =0.6V, the actual peak voltage dropped across the load will be:

$$V_L = V_{pk} - V_\gamma$$

$$V_L = 7.07 - 0.6$$

$$V_L = 6.47\ V$$

1.1.3 Reservoir and smoothing circuits

- Fig. 1.7 shows a simple half-wave rectifier circuit with reservoir capacitor.

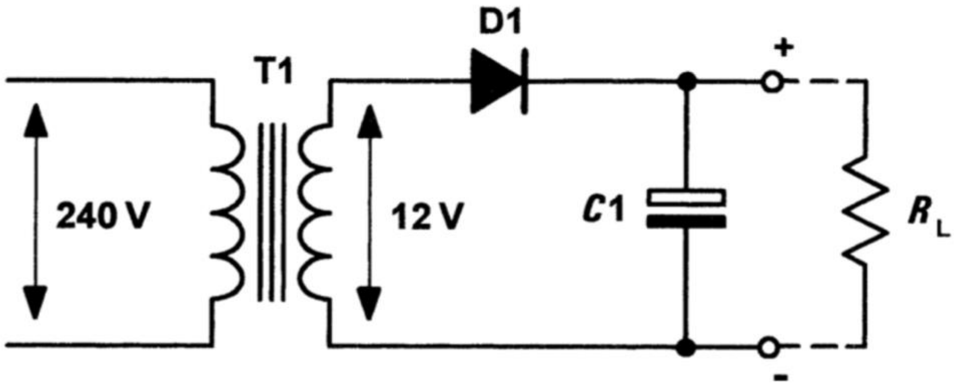


Figure 1.7 A simple half-wave rectifier circuit with reservoir capacitor

- The capacitor, C1, has been added to ensure that the output voltage remains at, or near, the peak voltage even when the diode is not conducting.
- When the primary voltage is first applied to T1, the first positive half-cycle output from the secondary will charge C1 to the peak value seen across R_L.
- Hence C1 charges to 16.3 V at the peak of the positive half-cycle. Because C1 and R_L are in parallel, the voltage across R_L will be the same as that across C1.

- The time required for C1 to charge to the maximum (peak) level is determined by the charging circuit time constant (the series resistance multiplied by the capacitance value).

- In this circuit, the series resistance comprises the secondary winding resistance together with the forward resistance of the diode and the (minimal) resistance of the wiring and connections. Hence C1 charges very rapidly as soon as D1 starts to conduct.

- The time required for C1 to discharge is, in contrast, very much greater. The discharge time constant is determined by the capacitance value and the load resistance, R_L. In practice, R_L is very much larger than the resistance of the secondary circuit and hence C1 takes an appreciable time to discharge. During this time, D1 will be reverse biased and will thus be held in its non-conducting state.

- As a consequence, the only discharge path for C1 is through R_L. C1 is referred to as a reservoir capacitor. It stores charge during the positive half-cycles of secondary voltage and releases it during the negative half-cycles.

- The circuit of Fig. 1.7 is thus able to maintain a reasonably constant output voltage across R_L. Even so, C1 will discharge by a small amount during the negative half-cycle periods from the transformer secondary.

- Fig. 1.8 shows the secondary voltage waveform together with the voltage developed across R_L with and without C1 present.

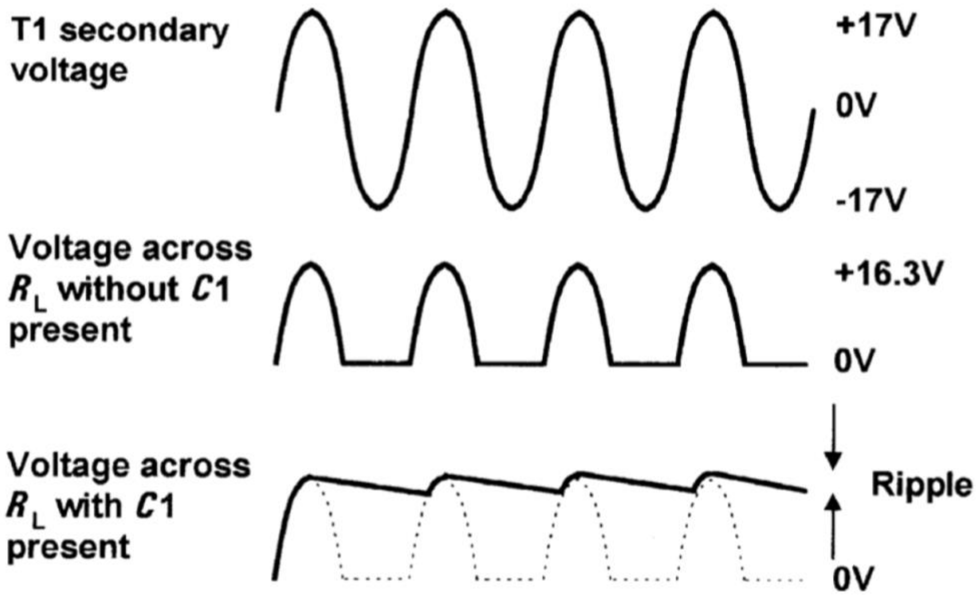


Figure 1.8 A simple half-wave rectifier circuit with reservoir capacitor

- This gives rise to a small variation in the d.c. output voltage (known as ripple). Since ripple is undesirable an additional precaution has to be taken to reduce it.

- One obvious method of reducing the amplitude of the ripple is that of simply increasing the discharge time constant. This can be achieved either by increasing the value of C1 or by increasing the resistance value of R_L.
- Fig. 1.9 shows a further refinement of the simple power supply circuit.

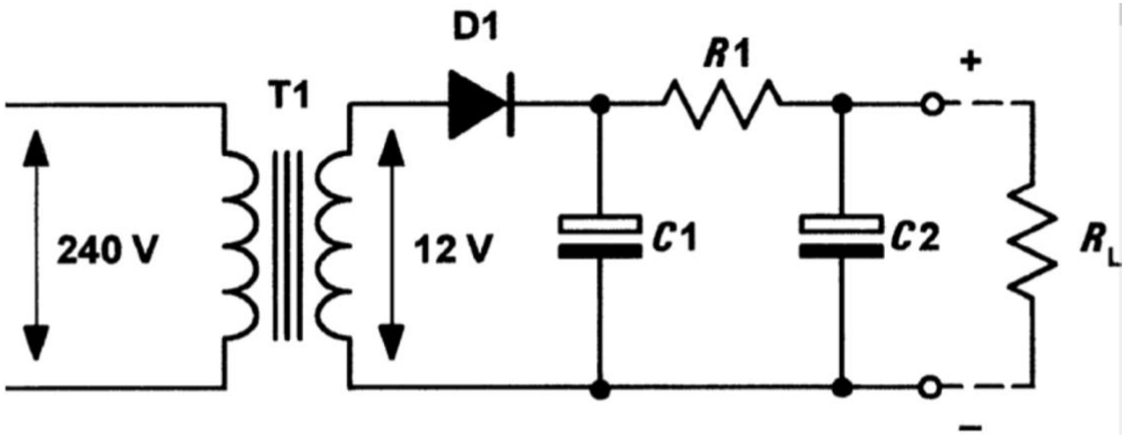


Figure 1.9 Half-wave rectifier circuit with R–C smoothing filter

- This circuit employs two additional components, R1 and C1, which act as a filter to remove the ripple.
- The value of C1 is chosen so that the component exhibits a negligible reactance at the ripple frequency (50 Hz for a half-wave rectifier or 100 Hz for a full-wave rectifier).
- In effect, R1 and C1 act like a potential divider. The amount of ripple is reduced by an approximate factor equal to:

$$\frac{X_C}{\sqrt{R^2 + X_C^2}}$$

Example 1.2

The R–C smoothing filter in a 50 Hz mains operated half-wave rectifier circuit consists of R1 = 100 Ω and C 2 = 1,000 μF. If 1 V of ripple appears at the input of the circuit, determine the amount of ripple appearing at the output.

Solution

First we must determine the reactance of the capacitor, C1, at the ripple frequency (50 Hz):

$$X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 50 \times 1{,}000 \times 10^{-6}}$$

$$= \frac{1{,}000}{314} = 3.18\ \Omega$$

The amount of ripple at the output of the circuit (i.e. appearing across $C1$) will be given by:

$$V_{ripple} = 1 \times \frac{X_C}{\sqrt{R^2 + X_C^2}} = 1 \times \frac{3.18}{\sqrt{100^2 + 3.18^2}}$$

From which:

$$V = 0.032\ \text{V} = 32\ \text{mV}$$

1.1.4 Full-wave rectifiers

- Unfortunately, the half-wave rectifier circuit is relatively inefficient as conduction takes place only on alternate half-cycles.
- A better rectifier arrangement would make use of both positive and negative half-cycles. These full-wave rectifier circuits offer a considerable improvement over their half-wave counterparts.
- They are not only more efficient but are significantly less demanding in terms of the reservoir and smoothing components.
- There are two basic forms of full wave rectifier:
  - i) Bi-phase rectifier
  - ii) Bridge rectifier

i) Bi-phase rectifier circuits

Fig. 1.10 shows a simple bi-phase rectifier circuit.

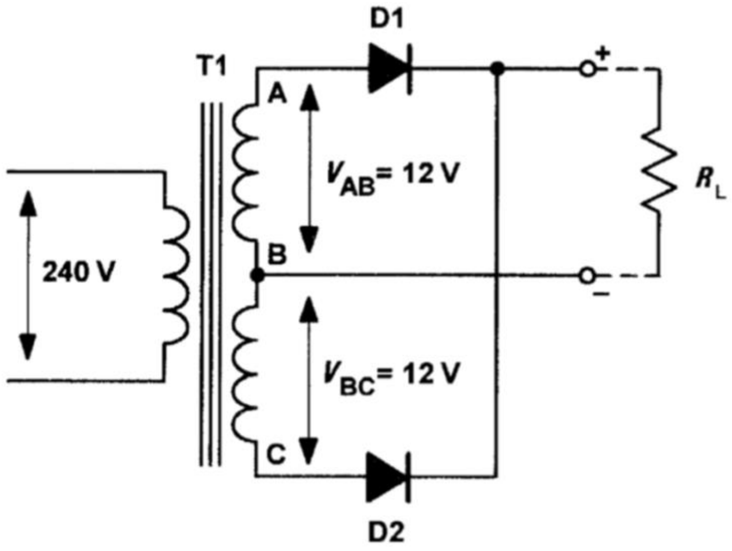


Figure 1.10 Bi-phase rectifier circuit

- Mains voltage (240 V) is applied to the primary of the step-down transformer (T1) which has two identical secondary windings, each providing 12 V r.m.s. (the turns ratio of T1 will thus be 240/12 or 20:1 for each secondary winding).
- On positive half-cycles, point A will be positive with respect to point B. Similarly, point B will be positive with respect to point C. In this condition D1 will allow conduction (its anode will be positive with respect to its cathode) while D2 will not allow conduction (its anode will be negative with respect to its cathode). Thus D1 alone conducts on positive half-cycles.
- On negative half-cycles, point C will be positive with respect to point B. Similarly, point B will be positive with respect to point A. In this condition D2 will allow conduction (its anode will be positive with respect to its cathode) while D1 will not allow conduction (its anode will be negative with respect to its cathode). Thus D2 alone conducts on negative half-cycles.
- Fig. 1.10 shows the bi-phase rectifier circuit with the diodes replaced by switches. In Fig. 1.11 (a) D1 is shown conducting on a positive half-cycle while in Fig. 1.11 (b) D2 is shown conducting.

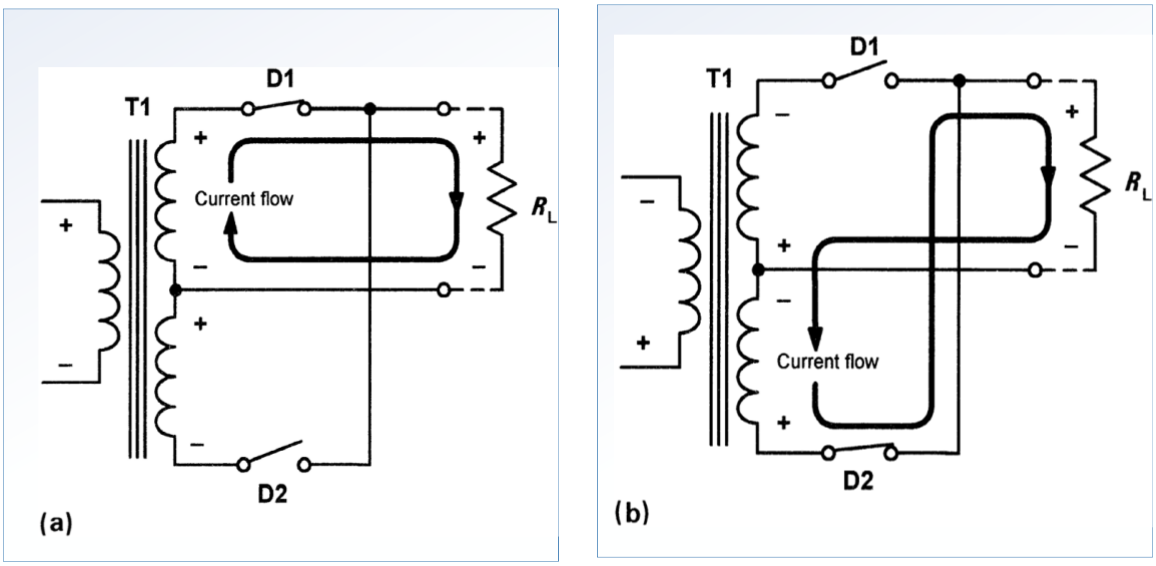


Figure 1.11 (a) Bi-phase rectifier with D1 conducting and D2 non-conducting
(b) bi-phase rectifier with D2 conducting and D1 non-conducting

- The result is that current is routed through the load in the same direction on successive half-cycles.
- Furthermore, this current is derived alternately from the two secondary windings. As with the half-wave rectifier, the switching action of the two diodes results in a pulsating output voltage being developed across the load resistor (R_L).
- However, unlike the half-wave circuit the pulses of voltage developed across RL will occur at a frequency of 100 Hz (not 50 Hz).
- This doubling of the ripple frequency allows us to use smaller values of reservoir and smoothing capacitor to obtain the same degree of ripple reduction.
- As before, the peak voltage produced by each of the secondary windings will be approximately 17 V and the peak voltage across RL will be 16.3 V (i.e. 17 V less the 0.7 V forward threshold voltage dropped by the diodes).
- Fig. 1.12 shows how a reservoir capacitor (C1) can be added to ensure that the output voltage remains at, or near, the peak voltage even when the diodes are not conducting.

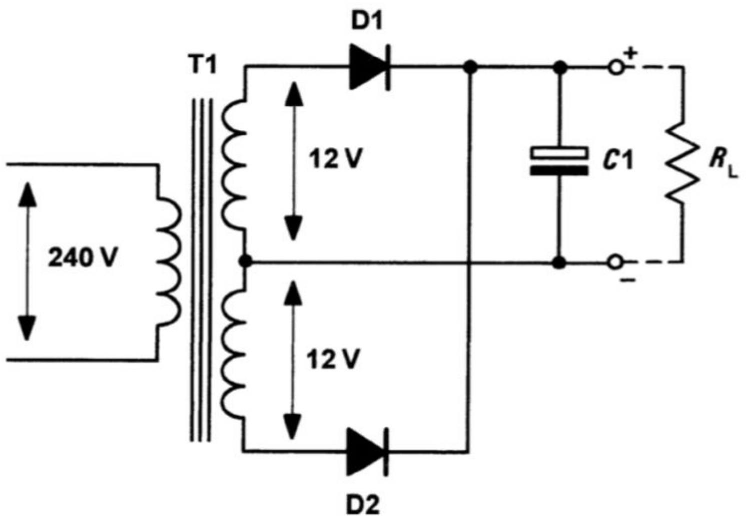


Figure 1.12 Bi-phase rectifier with reservoir capacitor

- This component operates in exactly the same way as for the half-wave circuit, i.e. it charges to approximately 16.3 V at the peak of the positive half-cycle and holds the voltage at this level when the diodes are in their non-conducting states.
- The time required for C1 to charge to the maximum (peak) level is determined by the charging circuit time constant (the series resistance multiplied by the capacitance value).
- In this circuit, the series resistance comprises the secondary winding resistance together with the forward resistance of the diode and the (minimal) resistance of the wiring and connections. Hence C1 charges very rapidly as soon as either D1 or D2 starts to conduct.
- The time required for C1 to discharge is, in contrast, very much greater. The discharge time contrast is determined by the capacitance value and the load resistance, R_L. In practice, R_L is very much larger than the resistance of the secondary circuit and hence C1 takes an appreciable time to discharge. During this time, D1 and D2 will be reverse biased and held in a non-conducting state.
- As a consequence, the only discharge path for C1 is through R_L. Fig. 1.13 shows voltage waveforms for the bi-phase rectifier, with and without C1 present.

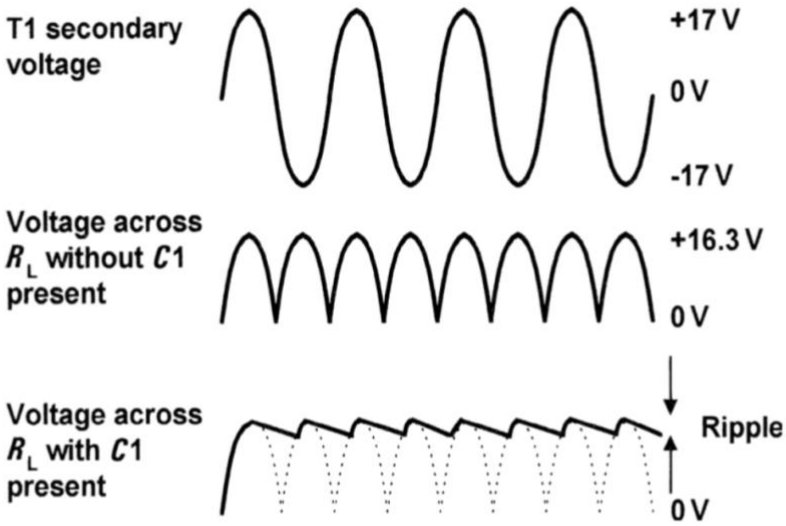


Figure 1.13 Waveforms for the bi-phase rectifier Note that the ripple frequency (100 Hz) is twice that of the half-wave circuit shown previously in Fig. 1.7.

ii) Bridge rectifier circuits

- An alternative to the use of the bi-phase circuit is that of using a four-diode bridge rectifier.
- A full-wave bridge rectifier arrangement is shown in Fig. 1.14.

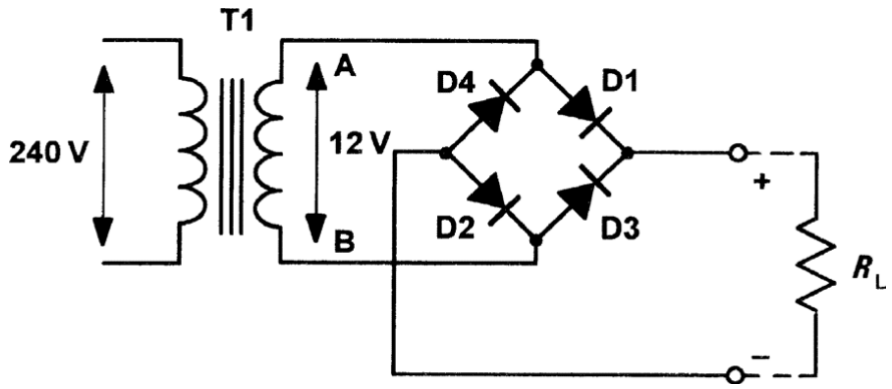
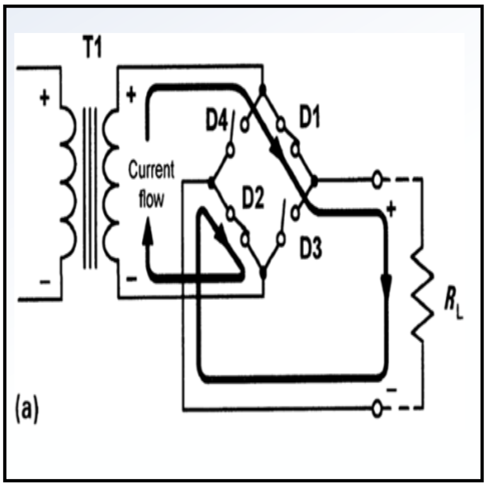


Figure 1.14 Full-wave bridge rectifier circuit

- Mains voltage (240 V) is applied to the primary of a step-down transformer (T1). The secondary winding provides 12 V r.m.s. (approximately 17 V peak) and has a turns ratio of 20:1, as before.
- On positive half-cycles, point A will be positive with respect to point B. In this condition D1 and D2 will allow conduction while D3 and D4 will not allow conduction.

- On negative half-cycles, point B will be positive with respect to point A. In this condition D3 and D4 will allow conduction while D1 and D2 will not allow conduction.
- Fig. 1.15 shows the bridge rectifier circuit with the diodes replaced by four switches. In Fig. 1.15(a) D1 and D2 are conducting on a positive half-cycle while in Fig. 1.15(b) D3 and D4 are conducting.



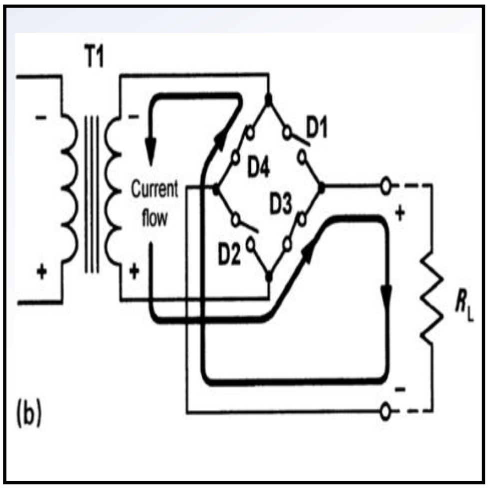


Figure 1.15 (a) Bridge rectifier with D1 and D2 conducting, D3 and D4 non-conducting (b) bridge rectifier with D1 and D2 non-conducting, D3 and D4 conducting

- Once again, the result is that current is routed through the load in the same direction on successive half-cycles.
- As with the bi-phase rectifier, the switching action of the two diodes results in a pulsating output voltage being developed across the load resistor (R_L). Once again, the peak output voltage is approximately 16.3 V (i.e. 17 V less the 0.7 V forward threshold voltage).
- Fig. 1.16 shows how a reservoir capacitor (C1) can be added to maintain the output voltage when the diodes are not conducting.

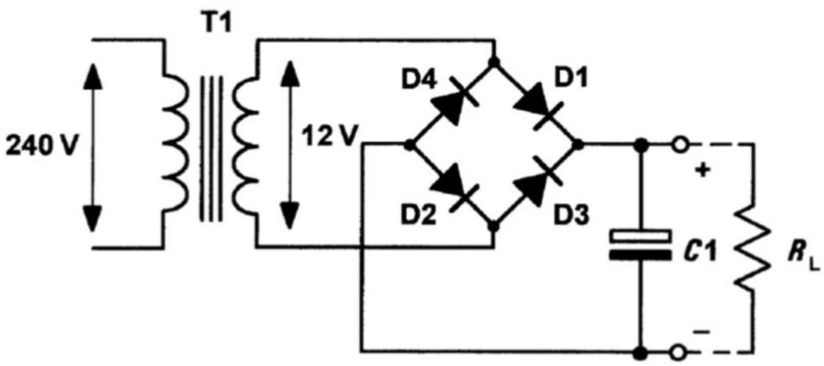


Figure 1.16 Bridge rectifier with reservoir

- This component operates in exactly the same way as for the bi-phase circuit, i.e. it charges to approximately 16.3 V at the peak of the positive half-cycle and holds the voltage at this level when the diodes are in their non-conducting states.
- The secondary and rectified output waveforms for the bridge rectifier are shown in Fig. 1.17.

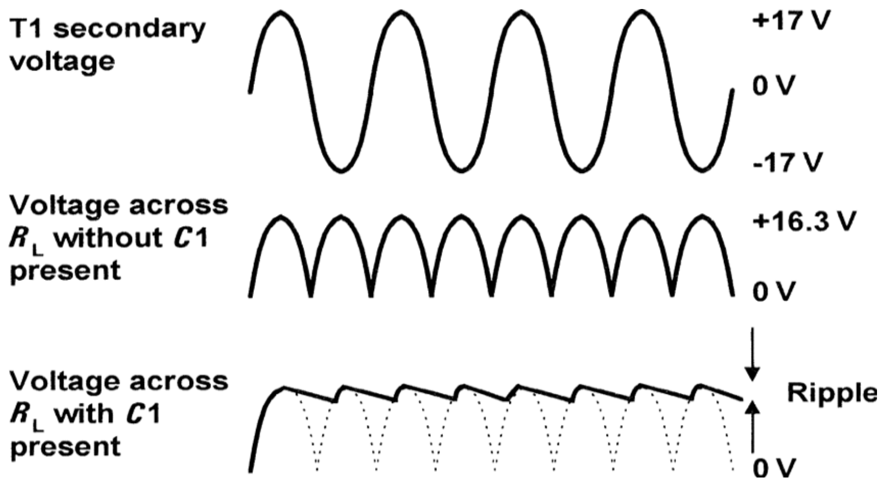


Figure 1.17 Waveforms for the bridge rectifier

- The ripple frequency is twice that of the incoming a.c. supply.
- Finally, R–C and L–C ripple filters can be added to bi-phase and bridge rectifier circuits in exactly the same way as those shown for the half-wave rectifier arrangement.

1.1.5 Voltage regulators

- Voltage regulator is a circuit that maintains a constant d.c output voltage irrespective of variations in the input line voltage or in the load.
- Voltage regulator is one of the important application of a Zener diode.
- A simple voltage regulator is shown in Fig. 1.18.

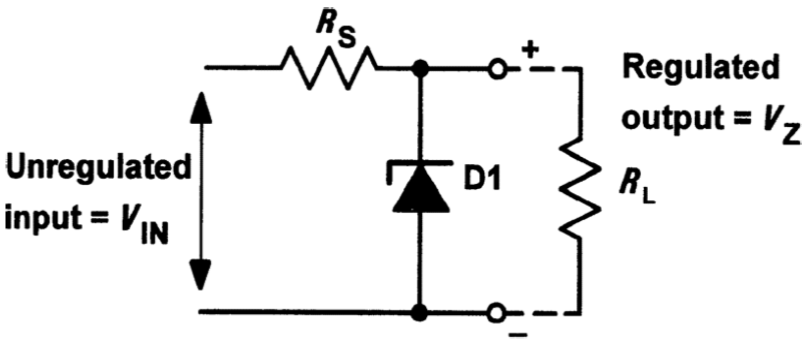


Figure 1.18 A simple shunt Zener voltage regulator

- R_S is included to limit the zener current to a safe value when the load is disconnected.
- When a load (R_L) is connected, the zener current (I_Z) will fall as current is diverted into the load resistance (it is usual to allow a minimum current of 2 mA to 5 mA in order to ensure that the diode regulates).
- The output voltage (V_Z) will remain at the Zener voltage until regulation fails at the point at which the potential divider formed by R_S and R_L produces a lower output voltage that is less than V_Z.
- The ratio of R_S to R_L is thus important.
- Regulated output V_Z is given by:

$$V_Z = V_{IN}\ X\ \frac{R_L}{R_L + R_S}$$

where V_{IN} is the unregulated input voltage.

- Thus the maximum value for R_S can be calculated from:

$$R_S\ \text{max.} = R_L \times \left(\frac{V_{IN}}{V_{IN}} - 1\right)$$

- The power dissipated in the zener diode will be given by $P_Z = I_Z \times V_Z$, hence the minimum value for R_S can be determined from the off-load condition when:

$$R_{S\,min.} = \left[\frac{V_{IN} - V_Z}{I_Z}\right] = \frac{V_{IN} - V_Z}{\left[\frac{P_{Z\,max.}}{V_Z}\right]} = \frac{(V_{IN} - V_Z)\ X\ V_Z}{P_{Z\,max.}}$$

$$\text{Thus: } R_{S\,min.} = \frac{V_{IN}\,V_Z - V_Z^2}{P_{Z\,max.}}$$

where P_Z max. is the maximum rated power dissipation for the zener diode.

Example 1.3

A 5 V zener diode has a maximum rated power dissipation of 500 mW. If the diode is to be used in a simple regulator circuit to supply a regulated 5 V to a load having a resistance of 400 Ω, determine a suitable value of series resistor for operation in conjunction with a supply of 9 V.

Solution

We shall use an arrangement similar to that shown in Fig. 6.19. First we should determine the maximum value for the series resistor, RS:

$$R_S \text{ max.} = R_L \times \left(\frac{V_{IN}}{V_{IN}} - 1\right)$$

thus:

$$R_S \text{ max.} = 400 \times \left(\frac{9}{5} - 1\right) = 400 \times (1.8 - 1) = 320\ \Omega$$

Now we need to determine the minimum value for the series resistor, R_S:

$$R_S \text{ min.} = \frac{V_{IN}V_Z - V_Z^2}{P_Z \text{ max.}}$$

thus:

$$R_S \text{ min.} = \frac{(9 \times 5) - 5^2}{0.5} = \frac{45 - 25}{0.5} = 40\ \Omega$$

Hence a suitable value for R_S would be 150 Ω (roughly mid-way between the two extremes).

1.1.6 Output resistance and voltage regulation

- In a perfect power supply, the output voltage would remain constant regardless of the current taken by the load.
- Output resistance R_{out} is defined as the change in output voltage divided by the corresponding change in output current and hence is given by:

$$Rout = \frac{change\ in\ output\ voltage}{change\ in\ output\ current} = \frac{\triangle V_{out}}{\triangle I_{out}}$$

where $\triangle I_{out}$ represents a small change in output (load) current and $\triangle V_{out}$ represents a corresponding small change in output voltage.

- The regulation of a power supply is given by the relationship:

$$Regulation\ =\frac{change\ in\ output\ voltage}{change\ in\ line\ (input)\ voltage}X\ 100\%$$

- Ideally, the value of regulation should be very small.
- Simple shunt zener diode regulators of the type shown in Fig. 1.17 are capable of producing values of regulation of 5% to 10%.
- More sophisticated circuits based on discrete components produce values of between 1% and 5% and integrated circuit regulators often provide values of 1% or less.

Example 1.4

The following data were obtained during a test carried out on a d.c. power supply:

(i) Load test
Output voltage (no-load) = 12 V
Output voltage (2 A load current) = 11.5 V

(ii) Regulation test

Output voltage (mains input, 220 V) = 12 V
Output voltage (mains input, 200 V) = 11.9 V

Determine (a) the equivalent output resistance of the power supply and (b) the regulation of the power supply.

Solution

The output resistance can be determined from the load test data:

$$Rout = \frac{change\ in\ output\ voltage}{change\ in\ output\ current} = \frac{12-11.5}{2-0} = 0.25\Omega$$

The regulation can be determined from the regulation test data:

$$Regulation\ =\frac{change\ in\ output\ voltage}{change\ in\ line\ (input)\ voltage}X\ 100\%$$

thus

$$Regulation\ =\frac{12-1.9}{220-200}X\ 100\% = \frac{0.1}{20}X\ 100\% = 0.5\%$$

1.1.7 Voltage multipliers

- By adding a second diode and capacitor, the output of the simple half-wave rectifier can be increased. A voltage doubler using this technique is shown in Fig. 1.19.

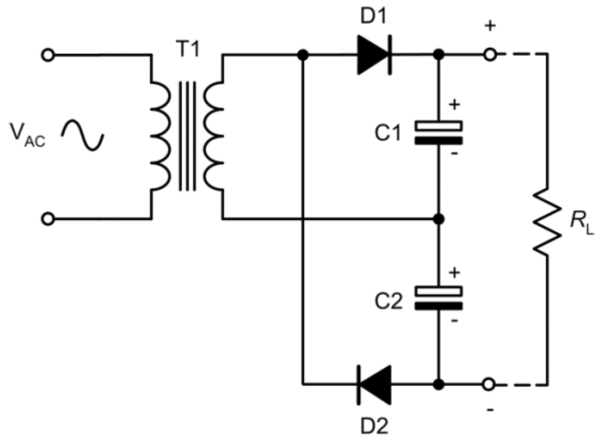


Figure 1.19 A voltage doubler

- In this arrangement C1 will charge to the positive peak secondary voltage while C2 will charge to the negative peak secondary voltage.
- Since the output is taken from C1 and C2 connected in series the resulting output voltage is twice that produced by one diode alone.
- The voltage doubler can be extended to produce higher voltages using the cascade arrangement shown in Fig. 1.20.

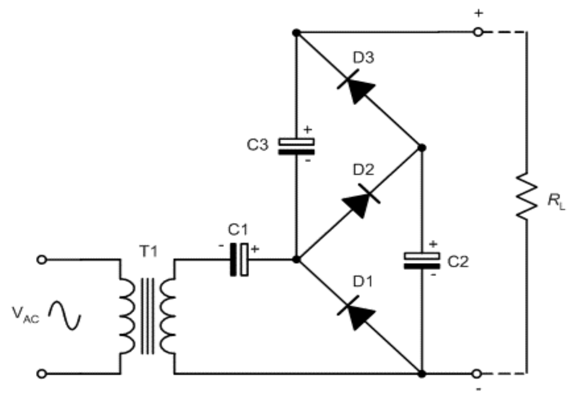


Figure 1.20 A voltage Tripler

- Here C1 charges to the positive peak secondary voltage, while C2 and C3 charge to twice the positive peak secondary voltage.

- The result is that the output voltage is the sum of the voltages across C1 and C3 which is three times the voltage that would be produced by a single diode.
- The ladder arrangement shown in Fig. 1.18 can be easily extended to provide even higher voltages but the efficiency of the circuit becomes increasingly impaired and high-order voltage multipliers of this type are only suitable for providing relatively small currents.

1.2 Amplifiers:

1.2.1 Types of amplifier

The following are the types of amplifiers:

1. a.c. coupled amplifiers

In a.c. coupled amplifiers, stages are coupled together in such a way that d.c. levels are isolated and only the a.c. components of a signal are transferred from stage to stage.

2. d.c. coupled amplifiers

In d.c. (or direct) coupled amplifiers, stages are coupled together in such a way that stages are not isolated to d.c. potentials. Both a.c. and d.c. signal components are transferred from stage to stage.

3. Large-signal amplifiers

Large-signal amplifiers are designed to cater for appreciable voltage and/or current levels (typically from 1 V to 100 V or more).

4. Small-signal amplifiers

Small-signal amplifiers are designed to cater for low-level signals (normally less than 1 V and often much smaller). Small-signal amplifiers have to be specially designed to combat the effects of noise.

5. Audio frequency amplifiers

Audio frequency amplifiers operate in the band of frequencies that is normally associated with audio signals (e.g. 20 Hz to 20 kHz).

6. Wideband amplifiers

Wideband amplifiers are capable of amplifying a very wide range of frequencies, typically from a few tens of hertz to several megahertz.

7. Radio frequency amplifiers

Radio frequency amplifiers operate in the band of frequencies that is normally associated with radio signals (e.g. from 100 kHz to over 1 GHz).

8. Low-noise amplifiers

Low-noise amplifiers are designed so that they contribute negligible noise (signal disturbance) to the signal being amplified. These amplifiers are usually designed for use with very small signal levels (usually less than 10 mV or so).

1.2.2 Class of operation

- The degree of linearity provided by an amplifier can be affected by a number of factors including the amount of bias applied and the amplitude of the input signal.
- Amplifiers are usually designed to be operated with a particular value of bias supplied to the active devices (i.e. transistors).
- For linear operation, the active device(s) must be operated in the linear part of their transfer characteristic (V_{out} plotted against V_{in}).

- In Fig. 1.21 the input and output signals for an amplifier are operating in linear mode.

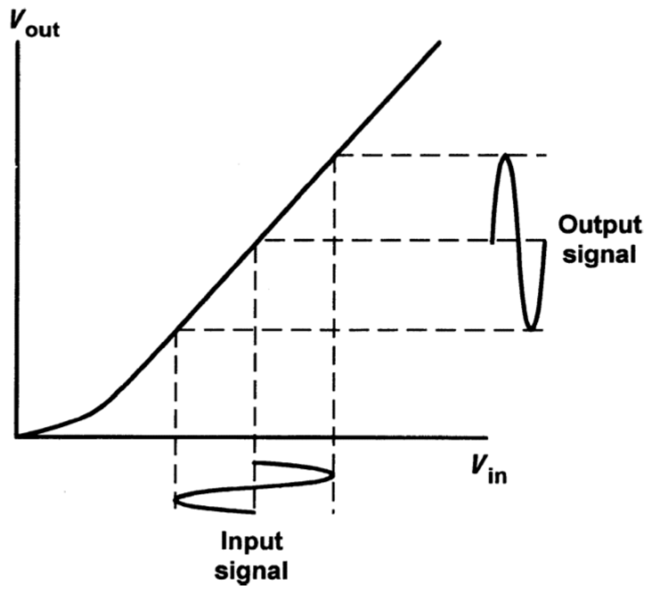


Figure 1.21 Class A (linear) operation

- This form of operation is known as Class A and the bias point is adjusted to the mid-point of the linear part of the transfer characteristic.
- Furthermore, current will flow in the active devices used in a Class A amplifier during a complete cycle of the signal waveform. At no time does the current fall to zero.
- Fig. 1.22 shows the effect of moving the bias point down the transfer characteristic and, at the same time, increasing the amplitude of the input signal.

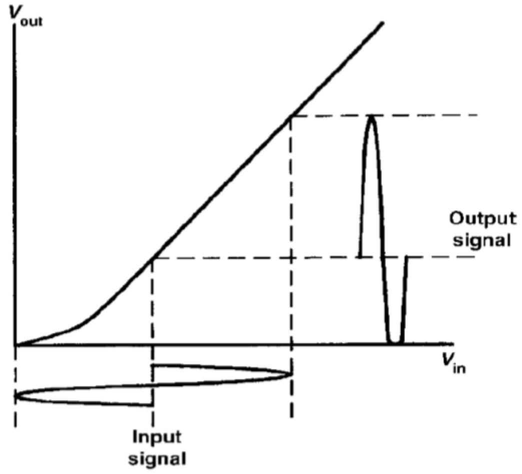


Figure 1.22 Effect of reducing bias and increasing input signal amplitude (the output waveform is no longer a faithful reproduction of the input)

- From this, the extreme negative portion of the output signal has become distorted. This effect arises from the non-linearity of the transfer characteristic that occurs near the origin (i.e. the zero point).
- Despite the obvious non-linearity in the output waveform, the active device(s) will conduct current during a complete cycle of the signal waveform.
- Now consider the case of reducing the bias even further while further increasing the amplitude of the input signal as shown in Fig. 1.23.

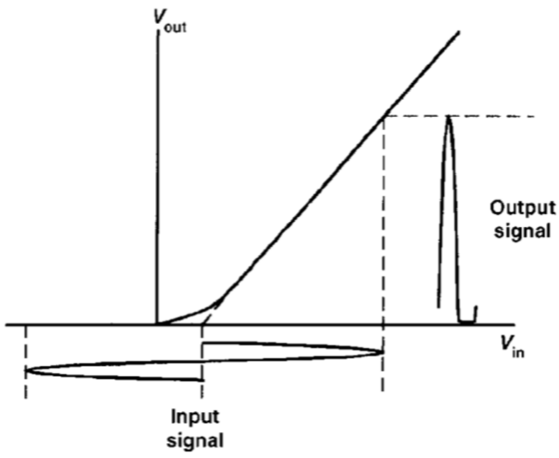


Figure 1.23 Class AB operation (bias set at projected cut-off)

- Here the bias point has been set at the projected cut-off point. The negative portion of the output signal becomes cut off (or clipped) and the active device(s) will cease to conduct for this part of the cycle. This mode of operation is known as Class AB.
- Now let's consider what will happen if no bias at all is applied to the amplifier as shown in Fig. 1.24.

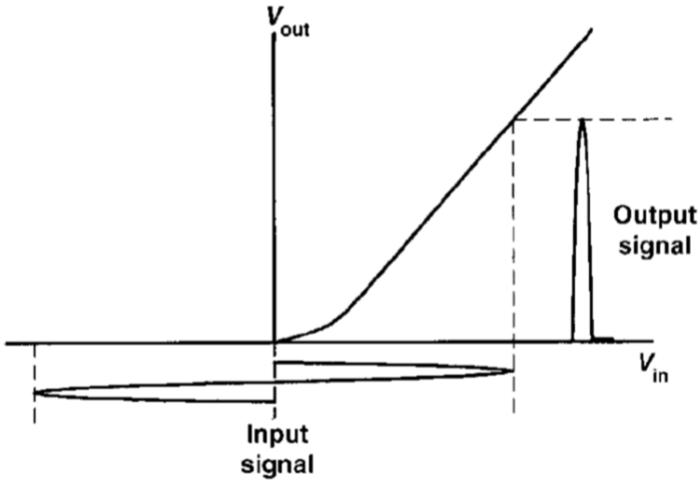


Figure 1.24 Class B operation (no bias applied)

- The output signal will only comprise a series of positive half-cycles and the active device(s) will only be conducting during half-cycles of the waveform (i.e. they will only be operating 50% of the time). This mode of operation is known as Class B and is commonly used in high-efficiency push-pull power amplifiers where the two active devices in the output stage operate on alternate half-cycles of the waveform.
- The input and output waveforms for Class C operation are shown in Fig. 1.25.

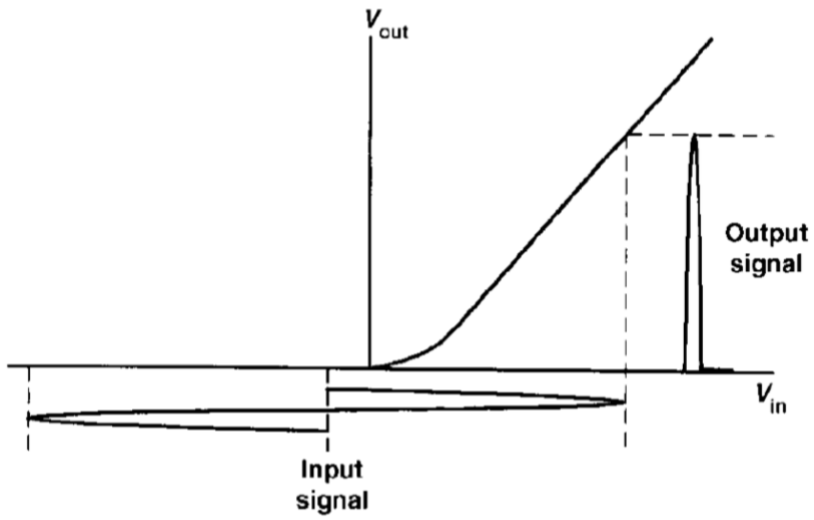


Figure 1.25 Class C operation (bias is set beyond cut-off)

- Here the bias point is set at beyond the cut-off (zero) point and a very large input signal is applied. The output waveform will then comprise a series of quite sharp positive-going pulses.
- These pulses of current or voltage can be applied to a tuned circuit load in order to recreate a sinusoidal signal.
- In effect, the pulses will excite the tuned circuit and its inherent flywheel action will produce a sinusoidal output waveform.
- This mode of operation is only used in RF power amplifiers that must operate at very high levels of efficiency.
- Table 1.1 summarizes the classes of operation used in amplifiers.

Table 1.1 Classes of operation

Class of operation	**Bias point**	**Conduction angle (typical)**	**Efficiency (typical)**	**Application**
A	Mid-point	360°	5% to 20%	Linear audio amplifiers

AB	Projected cut-off	210°	20% to 40%	Push–pull audio amplifiers
B	At cut-off	180°	40% to 70%	Push–pull audio amplifiers
C	Beyond cut-off	120°	70% to 90%	Radio frequency power amplifiers

1.2.3 Input and output resistance

- Input resistance is the ratio of input voltage to input current and it is expressed in ohms.
- The input of an amplifier is normally purely resistive (i.e. any reactive component is negligible) in the middle of its working frequency range (i.e. the mid-band).
- Output resistance is the ratio of open-circuit output voltage to short-circuit output current and is measured in ohms.
- Fig. 1.26 shows how the input and output resistances are 'seen' looking into the input and output terminals, respectively.

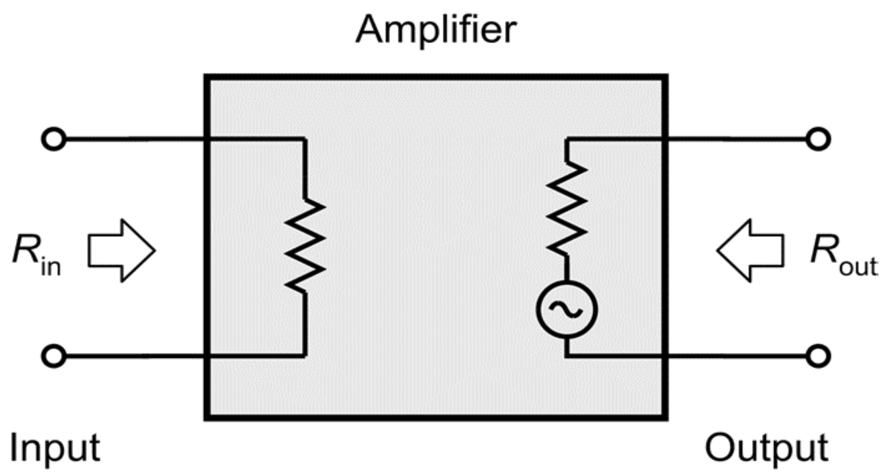


Figure 1.26 The Input and output resistance, with the input and output terminals, respectively.

1.2.4 Frequency response

- The frequency response characteristics for various types of amplifier are shown in Fig. 1.27.

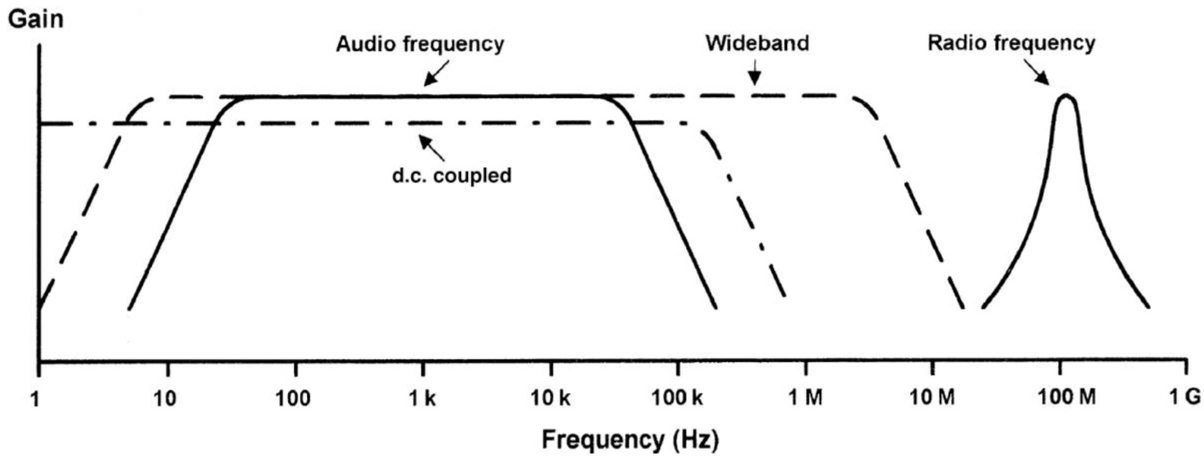


Figure 1.27 Frequency response and bandwidth (output power plotted against frequency)

- The frequency response of an amplifier is usually specified in terms of the upper and lower cut-off frequencies of the amplifier.
- These frequencies are those at which the output power has dropped to 50% (otherwise known as the −3 dB points) or where the voltage gain has dropped to 70.7% of its mid-band value.
- Figs 1.28 and 1.29, respectively, show how the bandwidth can be expressed in terms of either power or voltage (the cut-off frequencies, f1 and f2, and bandwidth are identical).

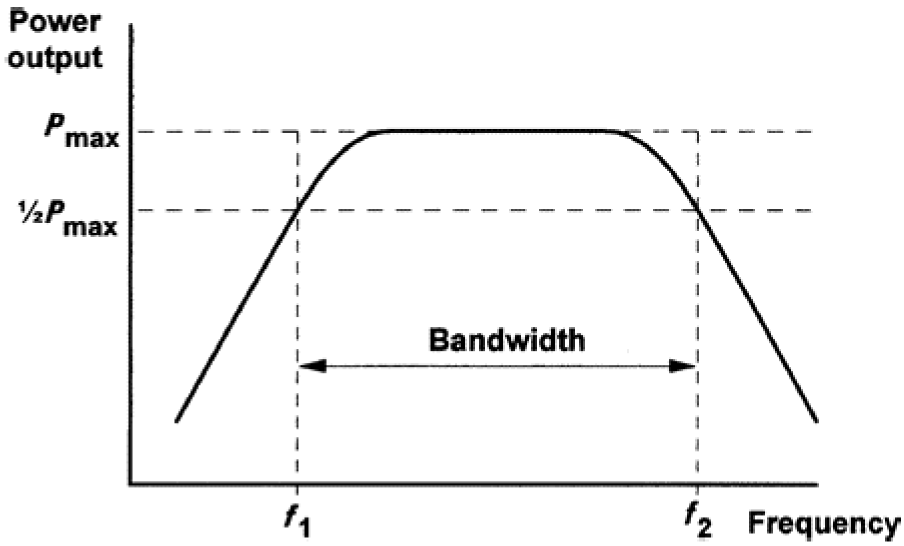


Figure 1.28 Frequency response and bandwidth (output power plotted against frequency)

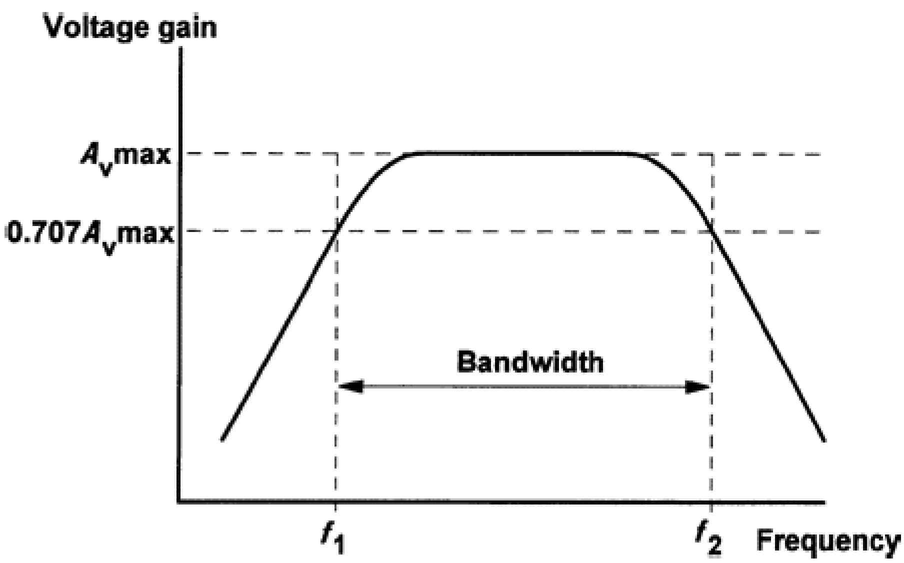
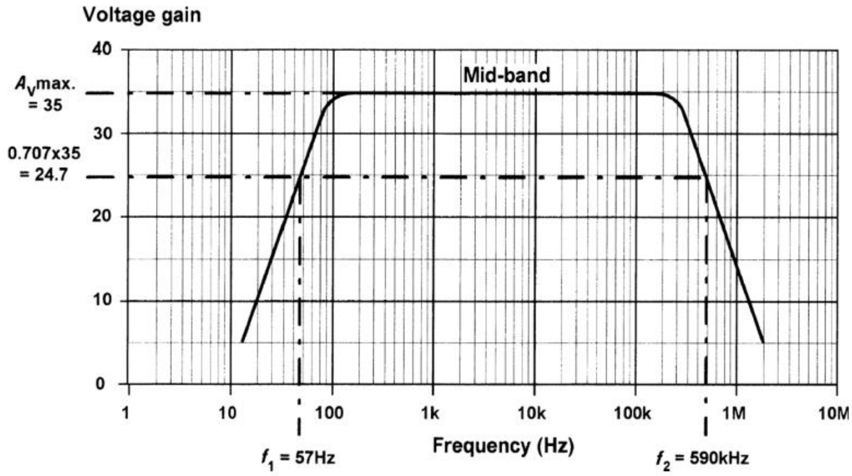


Figure 1.29 Frequency response and bandwidth (output voltage plotted against frequency)

Example 1.5

Determine the mid-band voltage gain and upper and lower cut-off frequencies for the amplifier whose frequency response is shown in figure below.



Solution

The mid-band voltage gain corresponds with the flat part of the frequency response characteristic. At that point the voltage gain reaches a maximum of 35.

The voltage gain at the two cut-off frequencies can be calculated from:

Av cut-off = 0.707 × Av max = 0.707 × 35 = 24.7

This value of gain intercepts the frequency response graph at f1 = 57 Hz and f2 = 590 kHz (see Fig. 7.12).

1.2.5 Bandwidth

- The bandwidth of an amplifier is usually taken as the difference between the upper and lower cut-off frequencies (i.e. f2 − f1 in Figs 7.10 and 7.11).

  Bandwidth = f2 – f1

- The bandwidth of an amplifier must be sufficient to accommodate the range of frequencies present within the signals that it is to be presented with.

- Many signals contain harmonic components (i.e. signals at 2f, 3f, 4f, etc. where f is the frequency of the fundamental signal).
- To reproduce a square wave, for example, requires an amplifier with a very wide bandwidth (note that a square wave comprises an infinite series of harmonics).

1.2.6 Phase shift

- Phase shift is the phase angle between the input and output signal voltages measured in degrees.
- The measurement is usually carried out in the mid-band where, for most amplifiers, the phase shift remains relatively constant.
- The conventional single-stage transistor amplifiers provide phase shifts of either 180° or 360°.

1.2.7 Negative feedback

- Many practical amplifiers use negative feedback in order to precisely control the gain, reduce distortion and improve bandwidth.
- The gain can be reduced to a manageable value by feeding back a small proportion of the output.
- The amount of feedback determines the overall (or closed-loop) gain. Because this form of feedback has the effect of reducing the overall gain of the circuit, this form of feedback is known as negative feedback.
- An alternative form of feedback, where the output is fed back in such a way as to reinforce the input (rather than to

subtract from it) is known as positive feedback. This form of feedback is used in oscillator circuits.

- Fig. 1.30 shows the block diagram of an amplifier stage with negative feedback applied.
- In this circuit, the proportion of the output voltage fed back to the input is given by β and the overall voltage gain will be given by: Overall gain, $G = \frac{V_{out}}{V_{in}}$

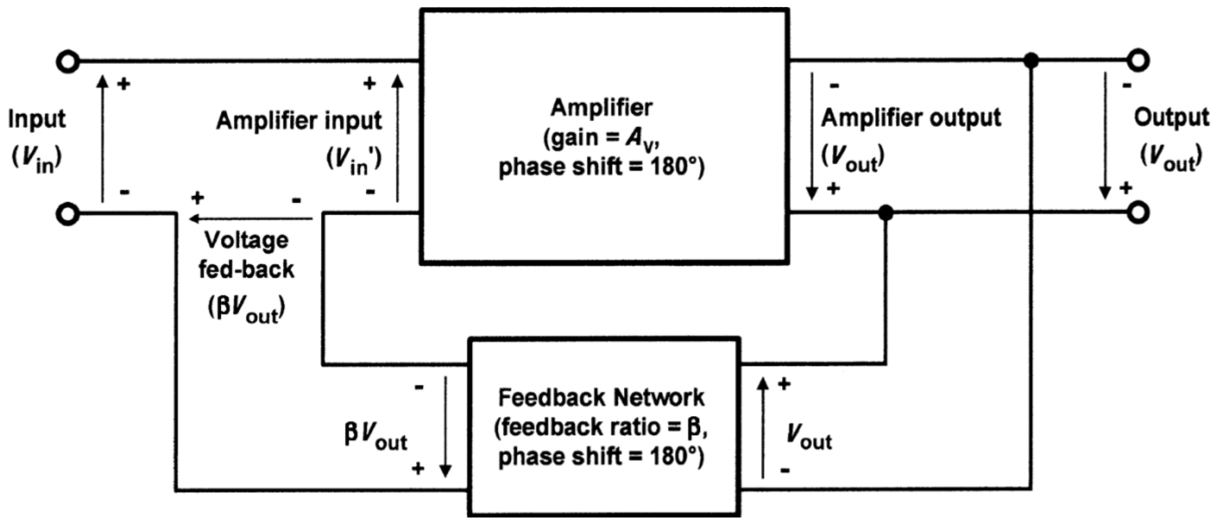


Figure 1.30 Amplifier with negative feedback applied

- Now $V_{in}' = V_{in} - \beta V_{out}$ (by applying Kirchhoff's Voltage Law) (note that the amplifier's input voltage has been reduced by applying negative feedback) thus:

$$V_{in} = V_{in}' + \beta V_{out}$$

and

$$V_{out} = A_v \times V_{in}$$

where, A_v is the internal gain of the amplifier

Hence:

$$\text{Overall gain, } G = \frac{A_V \; X \; V_{in}'}{V_{in}' + \beta V_{out}} = \frac{A_V \; X \; V_{in}'}{V_{in}' + \beta(A_V \; X \; V_{in}')}$$

Thus:

$$G = \frac{A_V}{1 + \beta A_V}$$

- Hence, the overall gain with negative feedback applied will be less than the gain without feedback.
- Furthermore, if Av is very large (as is the case with an operational amplifier) the overall gain with negative feedback applied will be given by:

$$G = 1/\beta \text{ (when Av is very large)}$$

- The loop gain of a feedback amplifier is defined as the product of β and Av.

Example 1.6

An amplifier with negative feedback applied has an open-loop voltage gain of 50, and one-tenth of its output is fed back to the input (i.e. β = 0.1). Determine the overall voltage gain with negative feedback applied.

Solution

With negative feedback applied the overall voltage gain will be given by:

$$G = \frac{A_v}{1+\beta A_v} = \frac{50}{1+(0.1\times 50)} = \frac{50}{6} = 8.33$$

Example 1.7

If, in Example 7.3, the amplifier's open-loop voltage gain increases by 20%, determine the percentage increase in overall voltage gain.

Solution

The new value of voltage gain will be given by:

Av = Av + 0.2Av = 1.2 × 50 = 60

The overall voltage gain with negative feedback will then be:

$$G = \frac{A_v}{1+\beta A_v} = \frac{60}{1+(0.1\times 60)} = \frac{60}{7} = 7.14$$

The increase in overall voltage gain, expressed as a percentage, will thus be:

$$\frac{8.57-8.33}{8.33}\times 100\% = 2.88\%$$

Note that this example illustrates one of the important benefits of negative feedback in stabilizing the overall gain of an amplifier stage.

Example 1.8

An integrated circuit that produces an open loop gain of 100 is to be used as the basis of an amplifier stage having a precise voltage gain of 20. Determine the amount of feedback required.

Solution

Re-arranging the formula,

Re-arranging the formula, $G = \frac{A_v}{1+\beta A_v}$ to make β the subject gives:

$$\beta = \frac{1}{G} - \frac{1}{A_v}$$

Thus:

$$\beta = \frac{1}{20} - \frac{1}{100} = 0.05 - 0.01 = 0.04$$

1.2.8 Multi-stage amplifiers

- To provide sufficiently large values of gain, it is frequently necessary to use a number of interconnected stages within an amplifier.
- The overall gain of an amplifier with several stages (i.e. a multi-stage amplifier) is simply the product of the individual voltage gains. Hence:

$$A_V = A_{V1} \times A_{V2} \times A_{V3}, \text{ etc.}$$

- The bandwidth of a multistage amplifier will be less than the bandwidth of each individual stage.
- An increase in gain can only be achieved at the expense of a reduction in bandwidth.
- Signals can be coupled between the individual stages of a multi-stage amplifier using one of a number of different methods shown in Fig. 1.27.

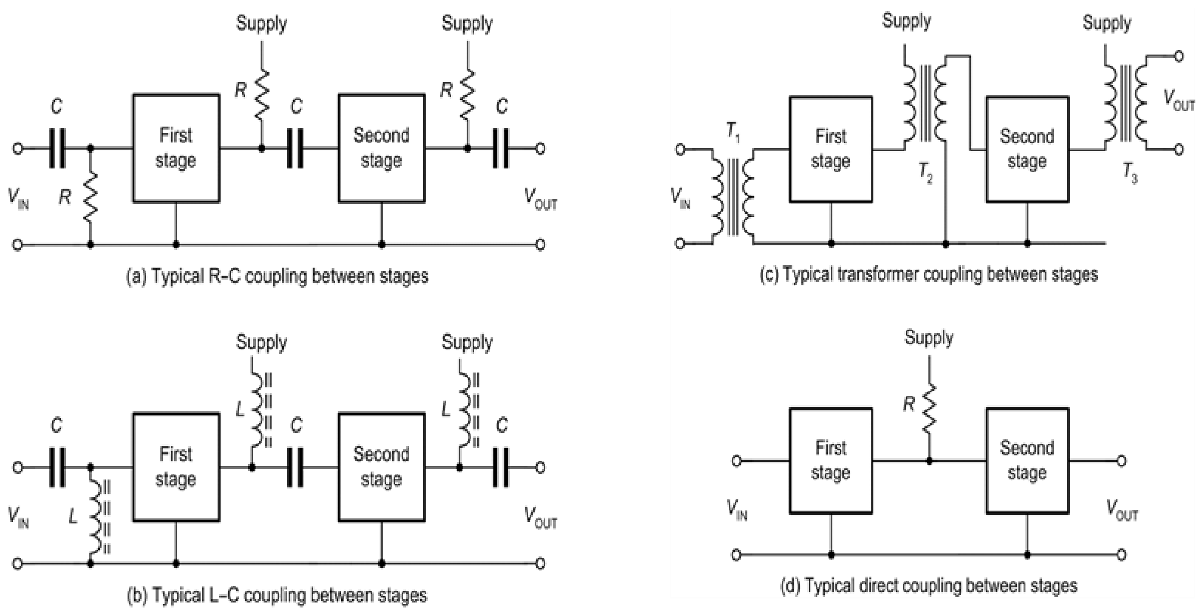


Figure 1.31 Different methods used for inter-stage coupling

- The most commonly used method is that of R–C coupling as shown in in Fig. 1.31 (a).

- In this coupling method, the stages are coupled together using capacitors having a low reactance at the signal frequency and resistors.
- Fig. 1.32 shows a practical example of this coupling method.

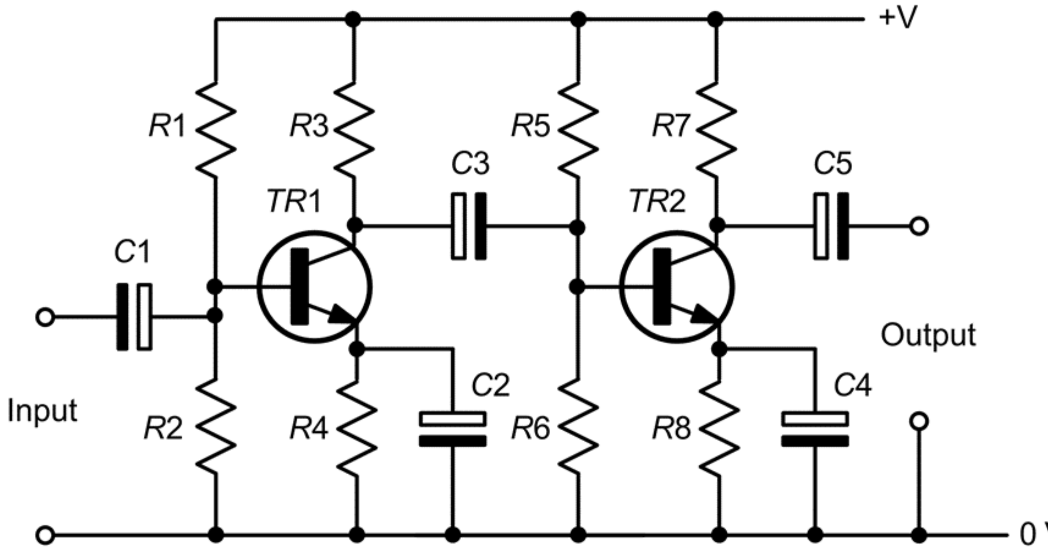


Figure 1.32 A typical two-stage high-gain R–C coupled common-emitter amplifier

- A similar coupling method, known as L–C coupling, is shown in Fig. 1.31 (b). In this method, the inductors have a high reactance at the signal frequency.
- This type of coupling is generally only used in RF and high-frequency amplifiers.
- Two further methods, transformer coupling and direct coupling, are shown in Figs 1.31 (c) and 1.31 (d), respectively.
- The latter method is used where d.c. levels present on signals must be preserved.

1.3 Operational Amplifiers:

Symbols and connections

- The symbol for an operational amplifier is shown in Fig. 1.33.

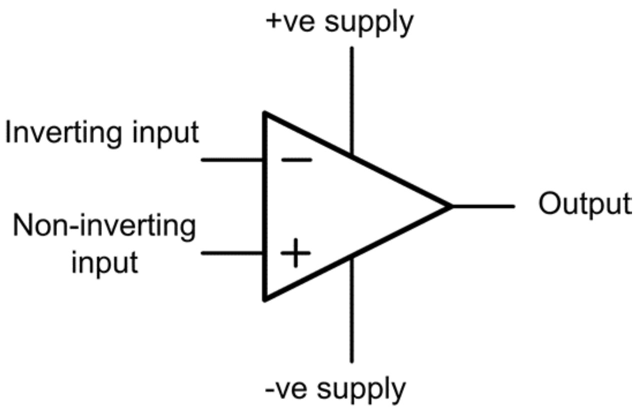


Figure 1.33 Symbol for an operational amplifier

- The device has two inputs and one output and no common connection. In Fig. 1.29, one of the inputs is marked '–' and the other is marked '+'. These polarity markings have nothing to do with the supply connections – they indicate the overall phase shift between each input and the output. The '+' sign indicates zero phase shift while the '–' sign indicates 180° phase shift.
- Since 180° phase shift produces an inverted waveform, the '–' input is often referred to as the inverting input. Similarly, the '+' input is known as the non-inverting input.
- Most of the operational amplifiers require a symmetrical supply (of typically ±6 V to ±15 V) which allows the output voltage to swing both positive (above 0 V) and negative (below 0 V).
- Fig. 1.34 shows how the supply connections for an operational amplifier.

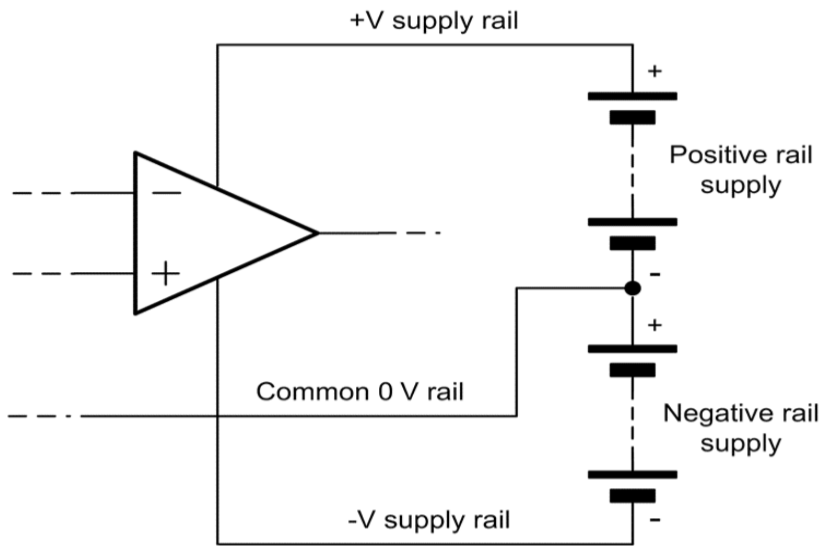


Figure 1.34 Supply connections for an operational amplifier

1.3.1 Operational amplifier parameters

Some of the terms and parameters of operational amplifier are discussed as follows:

a) Open-loop voltage gain

- The open-loop voltage gain of an operational amplifier is defined as the ratio of output voltage to input voltage measured with no feedback applied.
- Open-loop voltage gain of the device is given by:

$$A_{V(OL)} = \frac{V_{OUT}}{V_{IN}}$$

where $A_{V(OL)}$ is the open-loop voltage gain, V_{OUT} and V_{IN} are the output and input voltages, respectively, under open-loop conditions.

- In linear voltage amplifying applications, a large amount of negative feedback will normally be applied and the open-loop voltage gain can be thought of as the internal voltage gain provided by the device.

- The open-loop voltage gain is often expressed in decibels (dB) rather than as a ratio. Thus:

$$A_{V(OL)} = 20\,log_{10}\frac{V_{OUT}}{V_{IN}}$$

- Most operational amplifiers have open-loop voltage gains of 90 dB or more.

b) Closed-loop voltage gain

- The closed-loop voltage gain of an operational amplifier is defined as the ratio of output voltage to input voltage measured with a small proportion of the output fed-back to the input (i.e. with feedback applied).
- The effect of providing negative feedback is to reduce the loop voltage gain to a value that is both predictable and manageable.
- Practical closed-loop voltage gains range from one to several thousand but note that high values of voltage gain may make unacceptable restrictions on bandwidth.
- Closed-loop voltage gain is once again the ratio of output voltage to input voltage but with negative feedback applied, hence:

$$A_{V(CL)} = \frac{V_{OUT}}{V_{IN}}$$

where $A_{V(CL)}$ is the open-loop voltage gain, V_{OUT} and V_{IN} are the output and input voltages, respectively, under closed-loop conditions.

- The closed-loop voltage gain is normally very much less than the open-loop voltage gains.

Example 1.9

An operational amplifier operating with negative feedback produces an output voltage of 2 V when supplied with an input of 400 µV. Determine the value of closed-loop voltage gain.

Solution

Now:

$$A_{V(CL)} = \frac{V_{OUT}}{V_{IN}}$$

Thus:

$$A_{V(CL)} = \frac{2}{400 \times 10^{-6}} = \frac{2 \times 10^{6}}{400} = 5{,}000$$

Expressed in decibels (rather than as a ratio) this is:

$$A_{V(CL)} = 20\log_{10}(5{,}000) = 20 \times 3.7 = 74 \text{ dB}$$

c) Input resistance

- The input resistance of an operational amplifier is defined as the ratio of input voltage to input current expressed in ohms.
- The input resistance of operational amplifiers is very much dependent on the semiconductor technology employed.
- In practice values range from about 2 MΩ for common bipolar types to over 1012 Ω for FET and CMOS devices.
- Input resistance is the ratio of input voltage to input current:

$$R_{IN} = \frac{V_{IN}}{I_{IN}}$$

where R_{IN} is the input resistance (in ohms), V_{IN} is the input voltage (in volts) and I_{IN} is the input current (in amps).

Example 1.10

An operational amplifier has an input resistance of 2 MΩ. Determine the input current when an input voltage of 5 mV is present.

Solution

Now: $R_{IN} = \frac{V_{IN}}{I_{IN}}$

Thus,

$$I_{IN} = \frac{V_{IN}}{R_{IN}} = \frac{5X10^{-3}}{2X10^{6}} = 2.5X10^{-9}\,A = 2.5nA$$

d) Output resistance

- The output resistance of an operational amplifier is defined as the ratio of open-circuit output voltage to short-circuit output current expressed in ohms.
- Typical values of output resistance range from less than 10 Ω to around 100 Ω, depending upon the configuration and amount of feedback employed.
- Output resistance is the ratio of open-circuit output voltage to short-circuit output current, hence:

$$R_{OUT} = \frac{V_{OUT(OC)}}{I_{OUT(OC)}}$$

where ROUT is the output resistance (in ohms), VOUT(OC) is the open-circuit output voltage (in volts) and IOUT(SC) is the short-circuit output current (in amps).

e) Input offset voltage

- An ideal operational amplifier would provide zero output voltage when 0V difference is applied to its inputs.
- In practice, due to imperfect internal balance, there may be some small voltage present at the output.
- The voltage that must be applied differentially to the operational amplifier input in order to make the output voltage exactly zero is known as the input offset voltage.
- Input offset voltage may be minimized by applying relatively large amounts of negative feedback or by using the offset null facility provided by a number of operational amplifier devices.
- Typical values of input offset voltage range from 1 mV to 15 mV.

f) Full-power bandwidth

- The full-power bandwidth for an operational amplifier is equivalent to the frequency at which the maximum undistorted peak output voltage swing falls to 0.707 of its low-frequency (d.c.) value.
- Typical full-power bandwidths range from 10 kHz to over 1 MHz for some high-speed devices.

g) Slew rate

- Slew rate is the rate of change of output voltage with time, when a rectangular step input voltage is applied (as shown in Fig. 1.35).

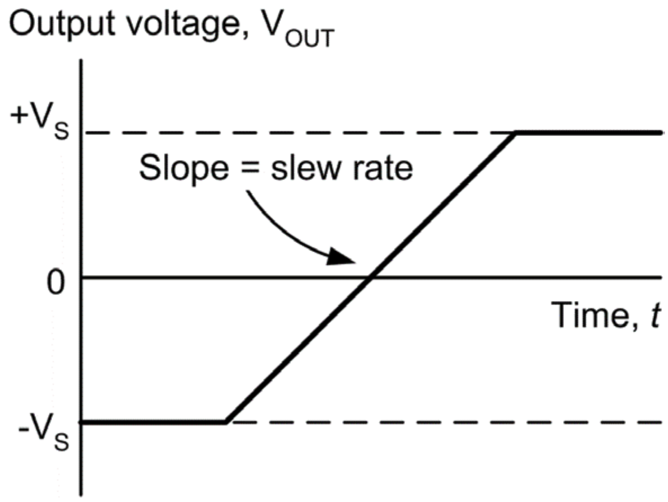


Figure 1.35 Slew rate for an operational amplifier

- The slew rate of an operational amplifier is the rate of change of output voltage with time in response to a perfect step-function input. Hence: $Slew\ rate = \frac{\triangle V_{OUT}}{\triangle t}$

where $\triangle V_{OUT}$ is the change in output voltage (in volts) and $\triangle t$ is the corresponding interval of time (in seconds).

- Slew rate is measured in V/s (or V/μs) and typical values range from 0.2 V/μs to over 20 V/μs.
- Slew rate imposes a limitation on circuits in which large amplitude pulses rather than small amplitude sinusoidal signals are likely to be encountered.

1.3.2 Operational amplifier characteristics

The following are the operational amplifier characteristics:

(a) The open-loop voltage gain should be very high (ideally infinite).

(b) The input resistance should be very high (ideally infinite).

(c) The output resistance should be very low (ideally zero).

(d) Full-power bandwidth should be as wide as possible.

(e) Slew rate should be as large as possible.

(f) Input offset should be as small as possible.

- The characteristics of most modern integrated circuit operational amplifiers (i.e. 'real' operational amplifiers) come very close to those of an 'ideal' operational amplifier, as witnessed by the data shown in Table 1.2.

Table 1.2 Comparison of operational amplifier parameters for 'ideal' and 'real' devices

Parameter	Ideal	Real
Voltage gain	Infinite	100,000
Input resistance	Infinite	100 MΩ
Output resistance	Zero	20 Ω
Bandwidth	Infinite	2 MHz
Slew rate	Infinite	10 V/μs
Input offset	Zero	Less than 5 mV

Example 1.11

A perfect rectangular pulse is applied to the input of an operational amplifier. If it takes 4 μs for the output voltage to change from –5 V to +5 V, determine the slew rate of the device.

Solution

The slew rate can be determined from:

$$Slew\ rate = \frac{\triangle V_{OUT}}{\triangle t} = \frac{10V}{4\mu s} = 2.5V/\mu s$$

Example 1.12

A wideband operational amplifier has a slew rate of 15 V/μs. If the amplifier is used in a circuit with a voltage gain of 20 and a perfect step input of 100 mV is applied to its input, determine the time taken for the output to change level.

Solution

The output voltage change will be 20 × 100 = 2,000 mV (or 2 V). Re-arranging the formula for slew rate gives:

$$\triangle t = \frac{\triangle V_{OUT}}{Slew\ rate} = \frac{2V}{15V/\mu s} = 0.133\mu s$$

1.3.3 Operational amplifier configurations

- The three basic configurations for operational voltage amplifiers, together with the expressions for their voltage gain, are shown in Fig. 1.36.

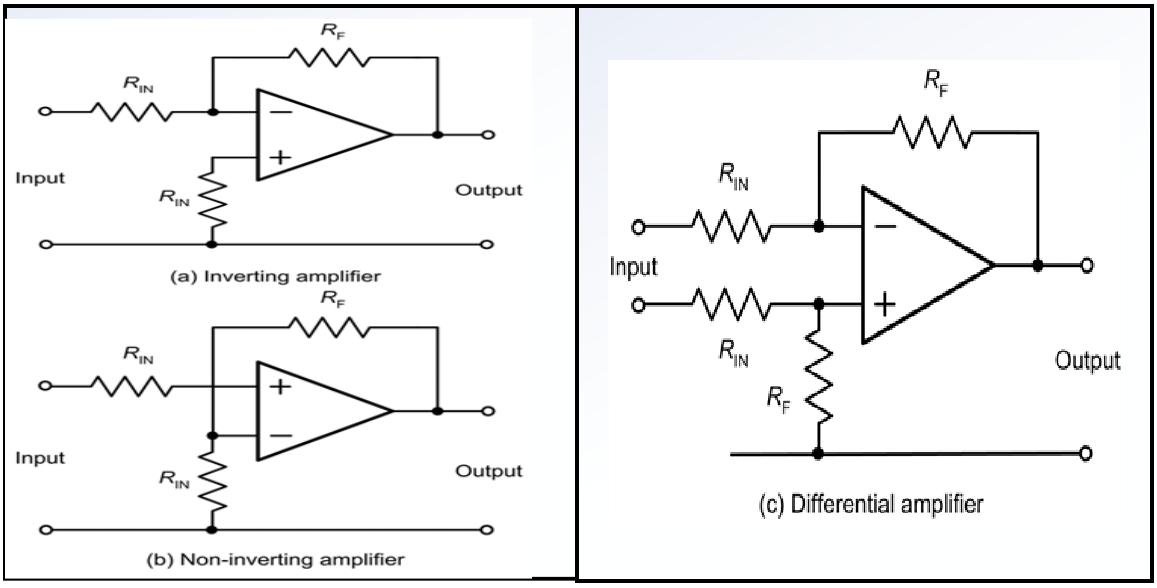


Figure 1.36 The three basic configurations for operational voltage amplifiers

- All of the amplifier circuits described previously have used direct coupling and thus have frequency response characteristics that extend to d.c.

- This, of course, is undesirable for many applications, particularly where a wanted a.c. signal may be superimposed on an unwanted d.c. voltage level or when the bandwidth of the amplifier greatly exceeds that of the signal that it is required to amplify.
- In such cases, capacitors of appropriate value may be inserted in series with the input resistor, R_{IN}, and in parallel with the feedback resistor, R_F, as shown in Fig. 1.37.

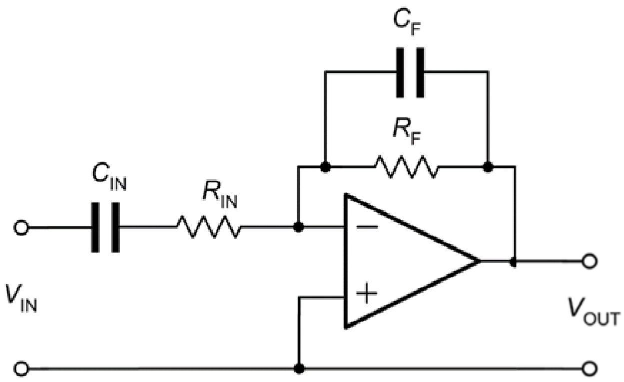


Figure 1.37 Adding capacitors to modify the frequency response of an inverting operational amplifier

- The value of the input and feedback capacitors, C_{IN} and C_F respectively, are chosen so as to roll-off the frequency response of the amplifier at the desired lower and upper cut-off frequencies, respectively.
- The effect of these two capacitors on an operational amplifier's frequency response is shown in Fig. 1.38.

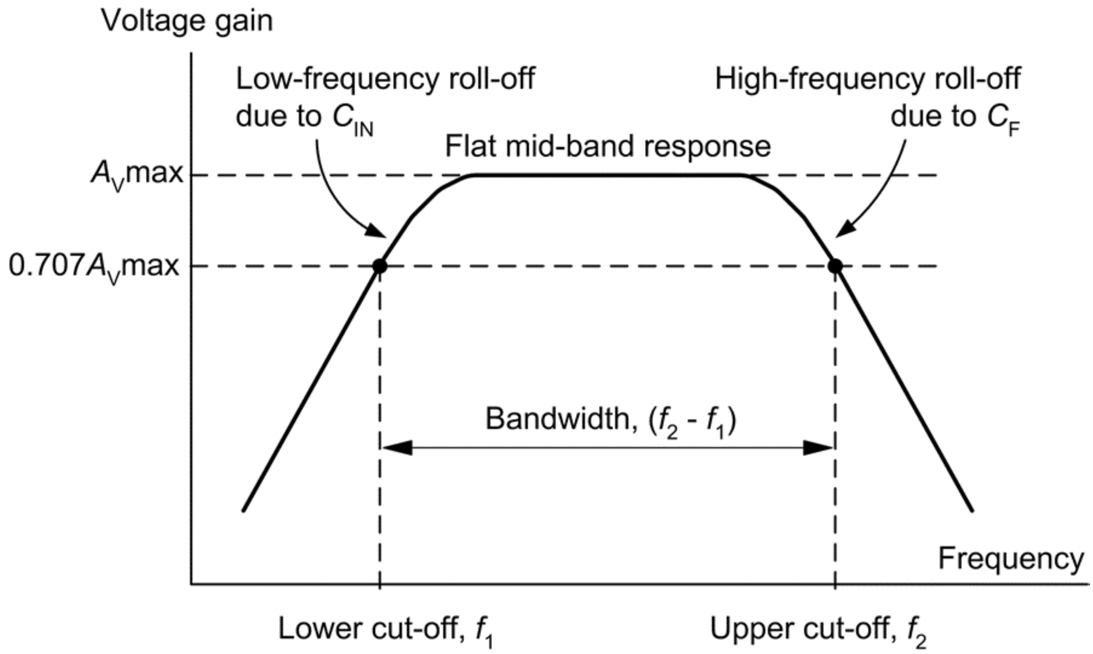


Figure 1.38 Effect of adding capacitors, C_{IN} and C_F, to modify the frequency response of an operational amplifier

- By selecting appropriate values of capacitor, the frequency response of an inverting operational voltage amplifier may be very easily tailored to suit a particular set of requirements.
- The lower cut-off frequency is determined by the value of the input capacitance, C_{IN}, and input resistance, R_{IN}. The lower cut-off frequency is given by:

$$f_1 = \frac{1}{2\pi C_{IN} R_{IN}} = \frac{0.159}{C_{IN} R_{IN}}$$

where f1 is the lower cut-off frequency in hertz, C_{IN} is in farads and R_{IN} is in ohms.

- Provided the upper frequency response it not limited by the gain × bandwidth product, the upper cut-off frequency will be determined by the feedback capacitance, C_F, and feedback resistance, R_F, such that:

$$f_2 = \frac{1}{2\pi C_F R_F} = \frac{0.159}{C_F R_F}$$

where f2 is the upper cut-off frequency in hertz, C_F is in farads and R_2 is in ohms.

Example 1.13

An inverting operational amplifier is to operate according to the following specification: Voltage gain = 100, Input resistance (at mid-band) = 10 kΩ, Lower cut-off frequency = 250 Hz, Upper cut-off frequency = 15 kHz. Devise a circuit to satisfy the above specification using an operational amplifier.

Solution

To make things a little easier, we can break the problem down into manageable parts. We shall base our circuit on a single operational amplifier configured as an inverting amplifier with capacitors to define the upper and lower cut-off frequencies, as shown in Fig. 8.9. The nominal input resistance is the same as the value for RIN. Thus: RIN = 10 kΩ

To determine the value of RF we can make use of the formula for mid-band voltage gain:

$$Av = R1/R2$$

thus R2 = Av × R1 = 100 × 10 kΩ = 100 kΩ To determine the value of CIN we will use the formula for the low-frequency cut-off:

$$f_1 = \frac{0.159}{C_{IN}R_{IN}}$$

from which:

$$C_{IN} = \frac{0.159}{f_1 R_{IN}} = \frac{0.159}{250 \times 10 \times 10^3}$$

hence:

$$C_{IN} = \frac{0.159}{2.5 \times 10^6} = 63 \times 10^{-9}\text{F} = 63\text{ nF}$$

Finally, to determine the value of C_F we will use the formula for high-frequency cut-off:

$$f_2 = \frac{0.159}{C_F R_F}$$

from which:

$$C_F = \frac{0.159}{f_2 R_{IN}} = \frac{0.159}{15 \times 10^3 \times 100 \times 10^3}$$

hence:

$$C_F = \frac{0.159}{1.5 \times 10^9} = 0.106 \times 10^{-9}\text{F} = 106\text{ pF}$$

For most applications the nearest preferred values (68 nF for CIN and 100 pF for CF) would be perfectly adequate. The complete circuit of the operational amplifier stage is shown in Fig. 1.39.

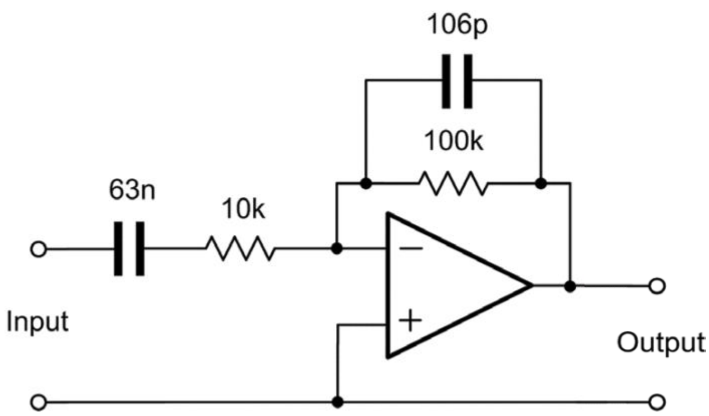


Figure 1.39 See Example 1.13. This operational amplifier has a mid-band voltage gain of 10 over the frequency range 250 Hz to 15 kHz

1.3.4 Operational amplifier circuits

- As well as their application as a general-purpose amplifying device, operational amplifiers have a number of other uses, including Voltage follower, Differentiator, Integrator, Comparator and Summing amplifier.

1. Voltage follower

- A voltage follower using an operational amplifier is shown in Fig. 1.40.

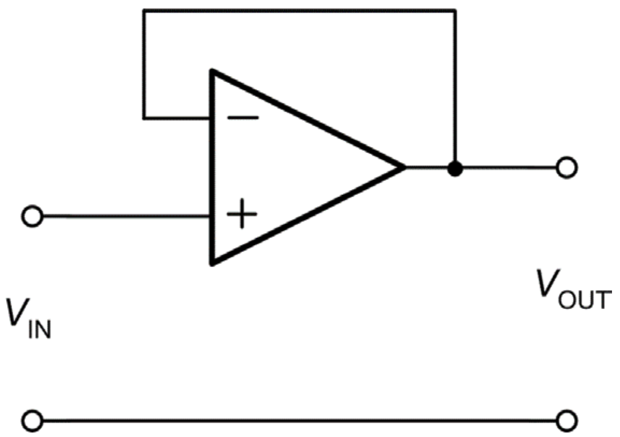


Figure 1.40 A voltage follower

- This circuit is essentially an inverting amplifier in which 100% of the output is fed back to the input.
- The result is an amplifier that has a voltage gain of 1 (i.e. unity), a very high input resistance and a very high output resistance.
- This stage is often referred to as a buffer and is used for matching a high-impedance circuit to a low-impedance circuit.
- Typical input and output waveforms for a voltage follower are shown in Fig. 1.41.

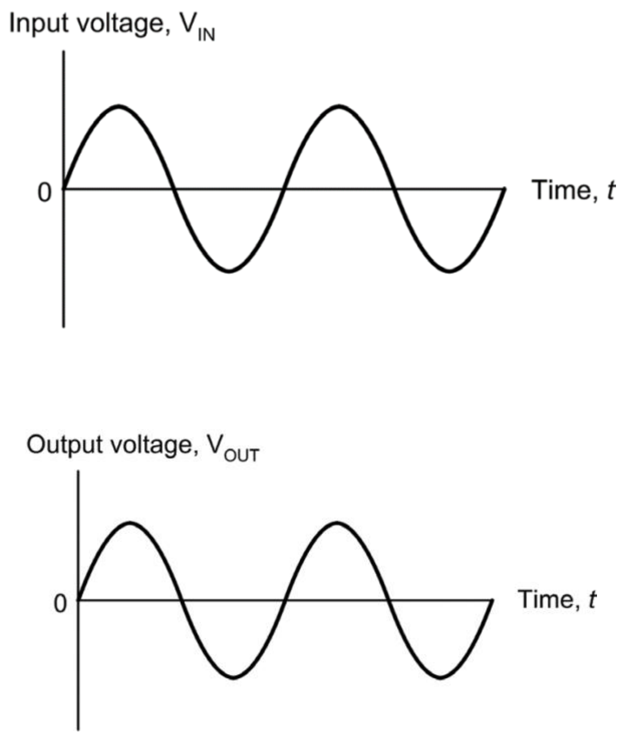


Figure 1.41 Typical input and output waveforms for a voltage follower

- The input and output waveforms are both in-phase (they rise and fall together) and that they are identical in amplitude.

2. Differentiator

- A differentiator using an operational amplifier is shown in Fig. 1.42.

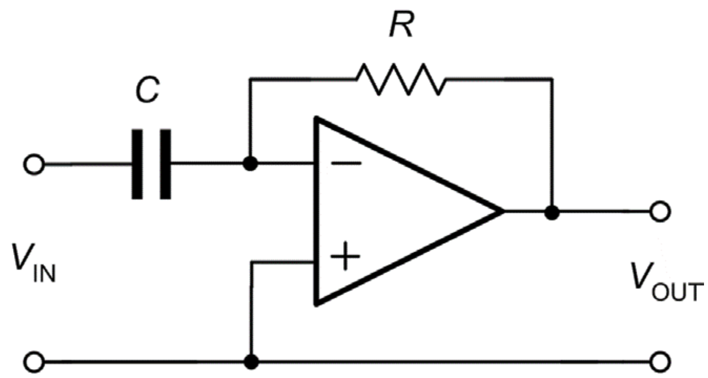


Figure 1.42 A differentiator

- A differentiator produces an output voltage that is equivalent to the rate of change of its input.
- In mathematics, this is equivalent to the differential function.
- Typical input and output waveforms for a differentiator are shown in Fig. 1.43.

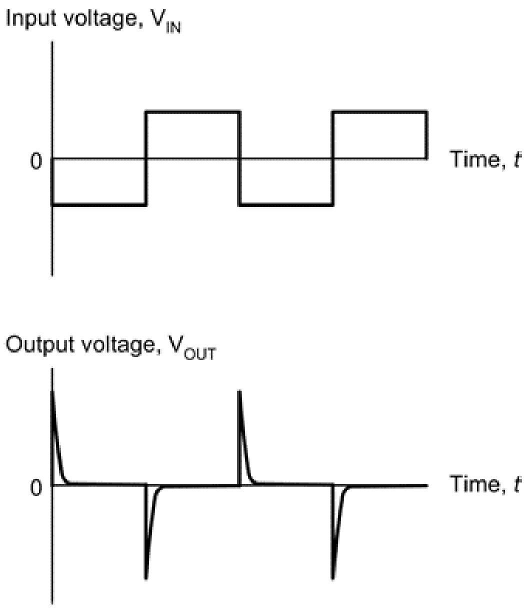


Figure 1.43 Typical input and output waveforms for a differentiator

- The square wave input is converted to a train of short duration pulses at the output.
- the output waveform is inverted because the signal has been applied to the inverting input of the operational amplifier.

3. Integrator

- An integrator using an operational amplifier is shown in Fig. 1.44.

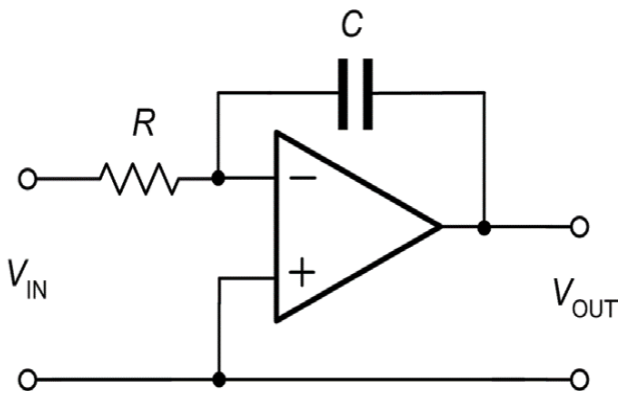


Figure 1.44 An integrator

- This circuit provides the opposite function to that of a differentiator in that its output is equivalent to the area under the graph of the input function rather than its rate of change.
- If the input voltage remains constant (and is other than 0 V) the output voltage will ramp up or down according to the polarity of the input.
- Typical input and output waveforms for an integrator are shown in Fig. 1.45.

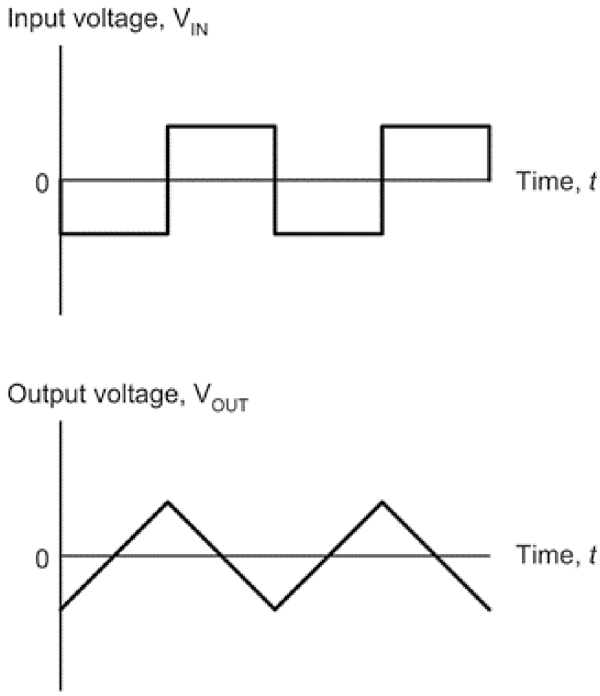


Figure 1.45 Typical input and output waveforms for an integrator

- The square wave input is converted to a wave that has a triangular shape and the output waveform is inverted.

4. Comparator

- A comparator using an operational amplifier is shown in Fig. 1.46.

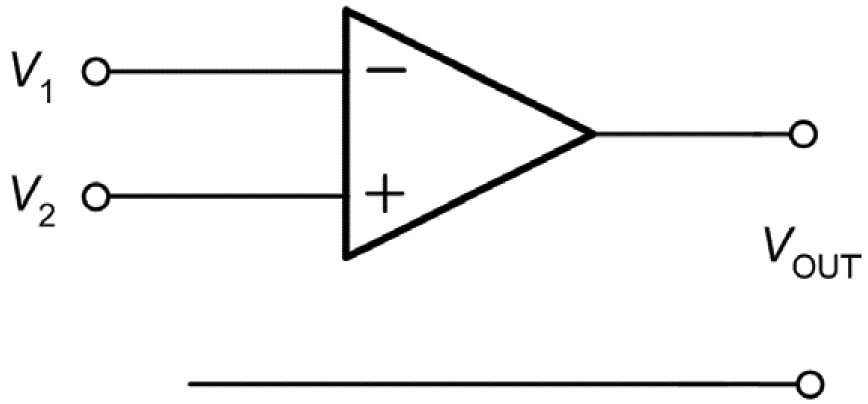


Figure 1.46 A comparator

- Since no negative feedback has been applied, the circuit uses the maximum gain of the operational amplifier.
- The output voltage produced by the operational amplifier will thus rise to the maximum possible value (equal to the positive supply rail voltage) whenever the voltage present at the non-inverting input exceeds that present at the inverting input.
- Conversely, the output voltage produced by the operational amplifier will fall to the minimum possible value (equal to the negative supply rail voltage) whenever the voltage present at the inverting input exceeds that present at the non-inverting input.
- Typical input and output waveforms for a comparator are shown in Fig. 1.47.

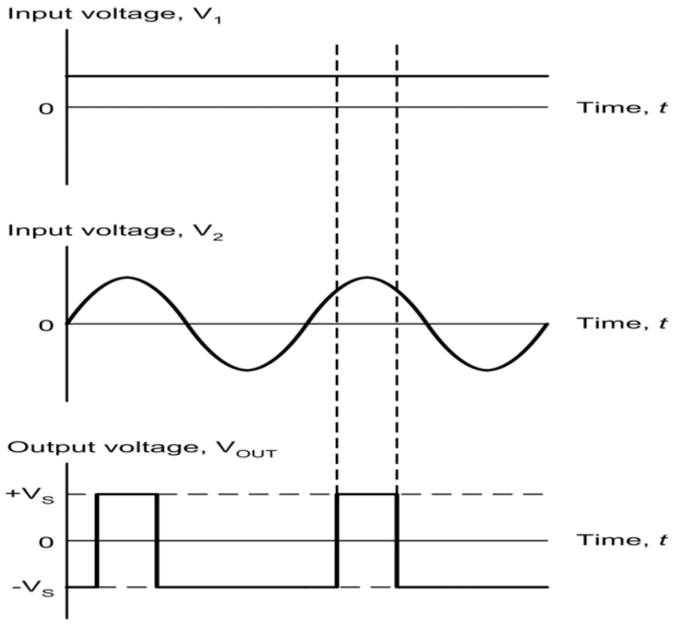


Figure 1.47 Typical input and output waveforms for a comparator

- The output is either +15 V or –15 V depending on the relative polarity of the two inputs.
- A typical application for a comparator is that of comparing a signal voltage with a reference voltage.
- The output will go high (or low) in order to signal the result of the comparison.

5. Summing amplifiers

- A summing amplifier using an operational amplifier is shown in Fig. 1.48.

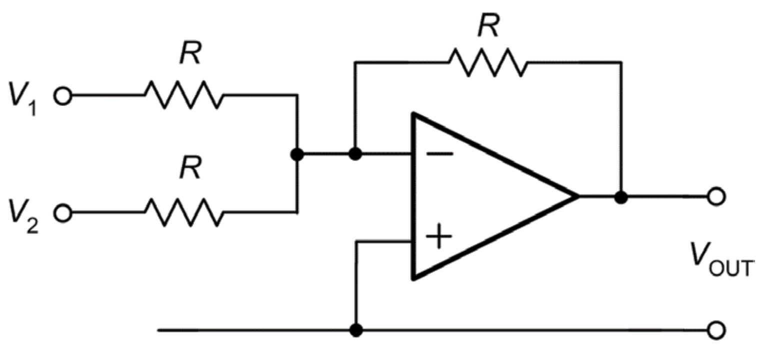


Figure 1.48 A summing amplifier

- This circuit produces an output that is the sum of its two input voltages.
- The input is connected to inverting terminal, so the output voltage is given by:

$$V_{OUT} = -(V_1 + V_2)$$

where V_1 and V_2 are the input voltages (note that all of the resistors used in the circuit have the same value).

- Typical input and output waveforms for a summing amplifier are shown in Fig. 1.49.

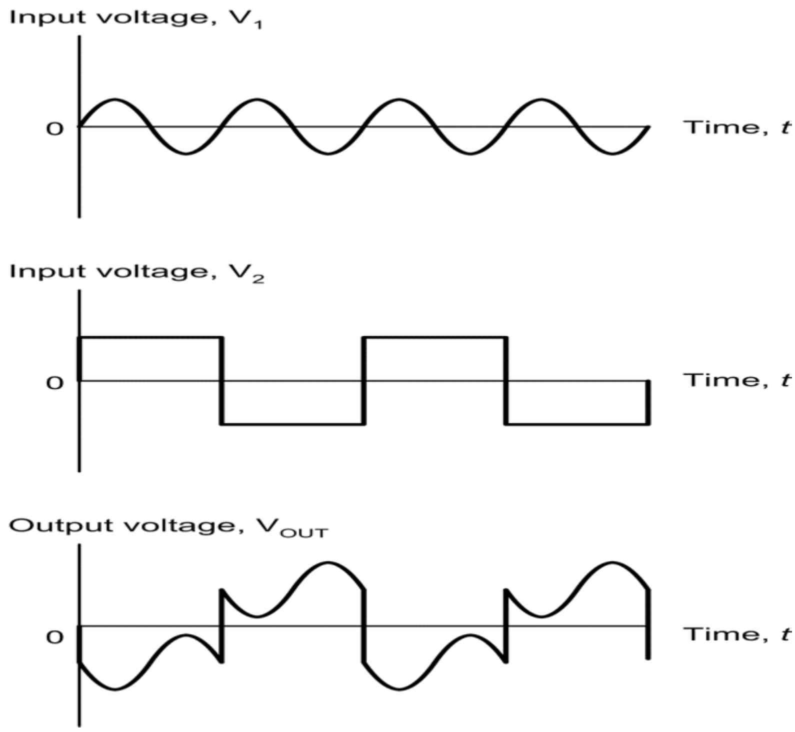


Figure 1.49 Typical input and output waveforms for a summing amplifier

- A typical application is that of 'mixing' two input signals to produce an output voltage that is the sum of the two.

1.4 Oscillators:

1.4.1 Positive feedback

- An alternative form of feedback, where the output is fed back in such a way as to reinforce the input (rather than to subtract from it), is known as positive feedback.
- Fig. 1.50 shows the block diagram of an amplifier stage with positive feedback applied.

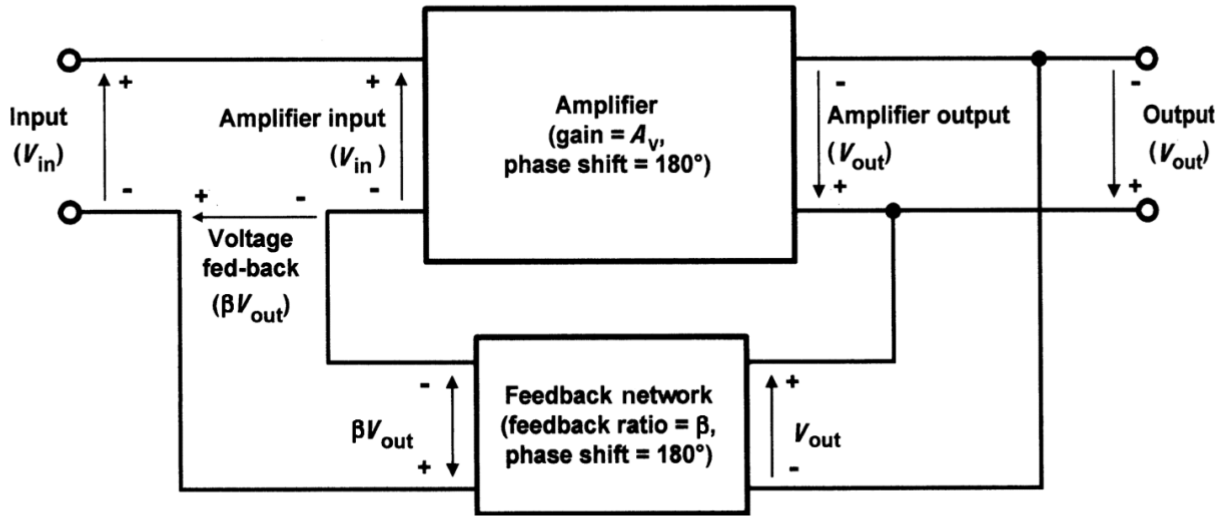


Figure 1.50 Amplifier with positive feedback applied

- The amplifier provides a phase shift of 180° and the feedback network provides a further 180°. Thus the overall phase shift is 0°.
- The overall gain, G, is given by:

$$G = \frac{V_{OUT}}{V_{IN}}$$

- By applying Kirchhoff's Voltage Law,

$$V'_{IN} = V_{IN} + \beta V_{OUT}$$

Thus:

$$V_{IN} = V'_{IN} - \beta V_{OUT}$$

and

$$V_{OUT} = A_V X\, V_{IN}$$

Where A_V is the internal gain of the amplifier.

Hence:

Overall gain,

$$G = \frac{A_V\ X\ V'_{IN}}{V'_{IN} - \beta V_{OUT}} - \frac{A_V\ X\ V'_{IN}}{V'_{IN} - \beta(A_V\ X\ V'_{IN})}$$

Thus,

$$G = \frac{A_V}{1 - \beta A_V}$$

- When the loop gain, βA_V, approaches unity (i.e. when the loop gain is just less than 1). The denominator (1 − βAv) will become close to zero.
- This will have the effect of increasing the overall gain, i.e. the overall gain with positive feedback applied will be greater than the gain without feedback.

1.4.2 Conditions for oscillation

The following are the conditions for oscillation:

(a) The feedback must be positive (i.e. the signal fed back must arrive back in-phase with the signal at the input).

(b) The overall loop voltage gain must be greater than 1 (i.e. the amplifier's gain must be sufficient to overcome the losses associated with any frequency selective feedback network).

- Hence, to create an oscillator an amplifier needs a sufficient gain to overcome the losses of the network that provide positive feedback.

1.4.3 Ladder network oscillator

- A simple phase-shift oscillator based on a three stage C–R ladder network is shown in Fig. 1.51.

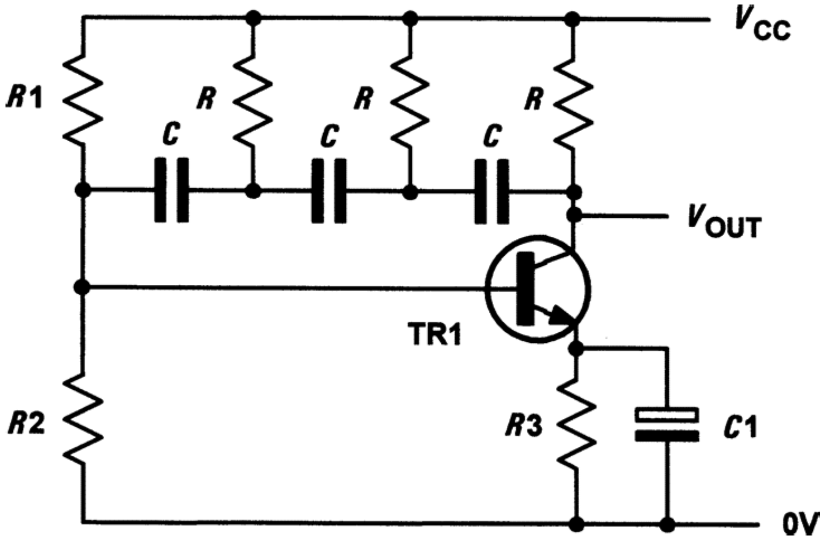


Figure 1.51 Sine wave oscillator based on a three stage C–R ladder network

- TR1 operates as a conventional common-emitter amplifier stage with R1 and R2 providing base bias potential and R3 and C1 providing emitter stabilization.
- The total phase shift provided by the C–R ladder network (connected between collector and base) is 180° at the frequency of oscillation.
- The transistor provides the other 180° phase shift in order to realize an overall phase shift of 360° or 0°.
- The frequency of oscillation of the circuit shown in Fig. 1.47 is given by:

$$G = \frac{A_V}{1 - \beta A_V}$$

$$f = \frac{1}{2\pi\, X \sqrt{6}\, CR}$$

- The loss associated with the ladder network is 29, thus the amplifier must provide a gain of at least 29 in order for the circuit to oscillate.

Example 1.14

Determine the frequency of oscillation of a three stage ladder network oscillator in which C = 10 nF and R = 10 kΩ.

Solution

Using

$$f = \frac{1}{2\pi \times \sqrt{6}CR}$$

gives

$$f = \frac{1}{6.28 \times 2.45 \times 10 \times 10^{-9} \times 10 \times 10^{3}}$$

from which

$$f = \frac{1}{6.28 \times 2.45 \times 10^{-4}} = \frac{10^4}{15.386} = 647 \text{ Hz}$$

1.4.4 Wien bridge oscillator

- An alternative approach to providing the phase shift required is the use of a Wien bridge network (Fig. 1.52).

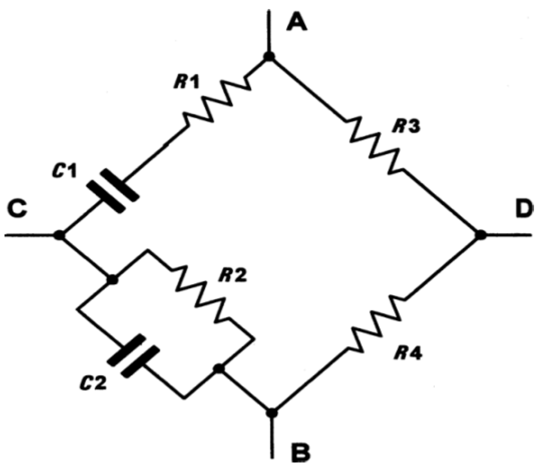


Figure 1.52 A Wien bridge network

- The input signal is applied to A and B while the output is taken from C and D.
- At one particular frequency, the phase shift produced by the network will be exactly zero (i.e. the input and output signals will be in-phase).
- The minimum amplifier gain required to sustain oscillation is given by:

$$A_V = 1 + \frac{C1}{C2} + \frac{R2}{R1}$$

- In most cases, C1 = C 2 and R1 = R2, hence the minimum amplifier gain will be 3.
- The frequency at which the phase shift will be zero is given by:

$$f = \frac{1}{2\pi\, X\, \sqrt{C1\, C2\, R1\, R2}}$$

when R1 = R2 and C1 = C2 the frequency at which the phase shift will be zero will be given by:

$$f = \frac{1}{2\pi\, X\, \sqrt{C^2 R^2}} = \frac{1}{2\pi CR}$$

where R = R1 = R2 and C = C1 = C2.

Example 1.15

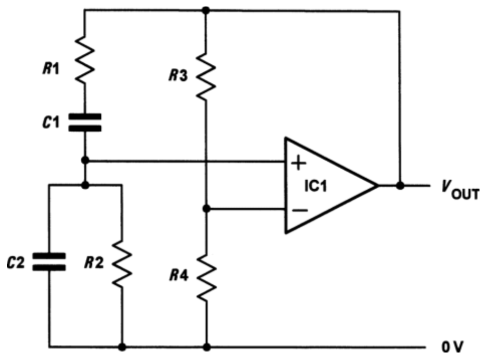


Figure 1.53 Sine wave oscillator based on a Wien bridge network

Fig. 1.53 shows the circuit of a Wien bridge oscillator based on an operational amplifier. If C1 = C 2 = 100 nF, determine the output frequencies produced by this arrangement (a) when R1 = R2 = 1 kΩ and (b) when R1 = R2 = 6 kΩ.

Solution

(a) When $R1 = R2 = 1$ kΩ

$$f = \frac{1}{2\pi CR}$$

where $R = R1 = R1$ and $C = C1 = C2$.

Thus

$$f = \frac{1}{6.28 \times 100 \times 10^{-9} \times 1 \times 10^{3}}$$

$$f = \frac{10^{4}}{6.28} = 1.59 \text{ kHz}$$

(b) When $R1 = R1 = 6$ kΩ

$$f = \frac{1}{2\pi CR}$$

where $R = R1 = R1$ and $C = C1 = C2$.

Thus

$$f = \frac{1}{6.28 \times 100 \times 10^{-9} \times 6 \times 10^{3}}$$

$$f = \frac{10^{4}}{37.68} = 265 \text{ Hz}$$