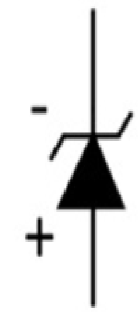


Unit 1
Electronic Circuits:

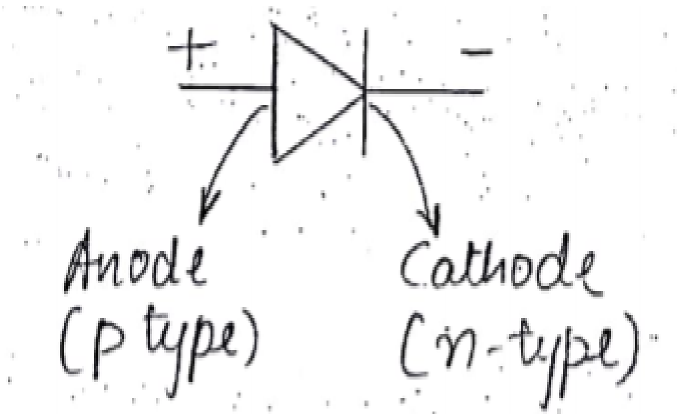
Pre requisites

- Semiconductor basics
- What is semiconductor?
- Why do we need semiconductor?
- Types of semiconductor- Intrinsic and Extrinsic
- Extrinsic- Doping, p type, n type- trivalent and pentavalent
- Majority and minority charge carriers

Syllabus

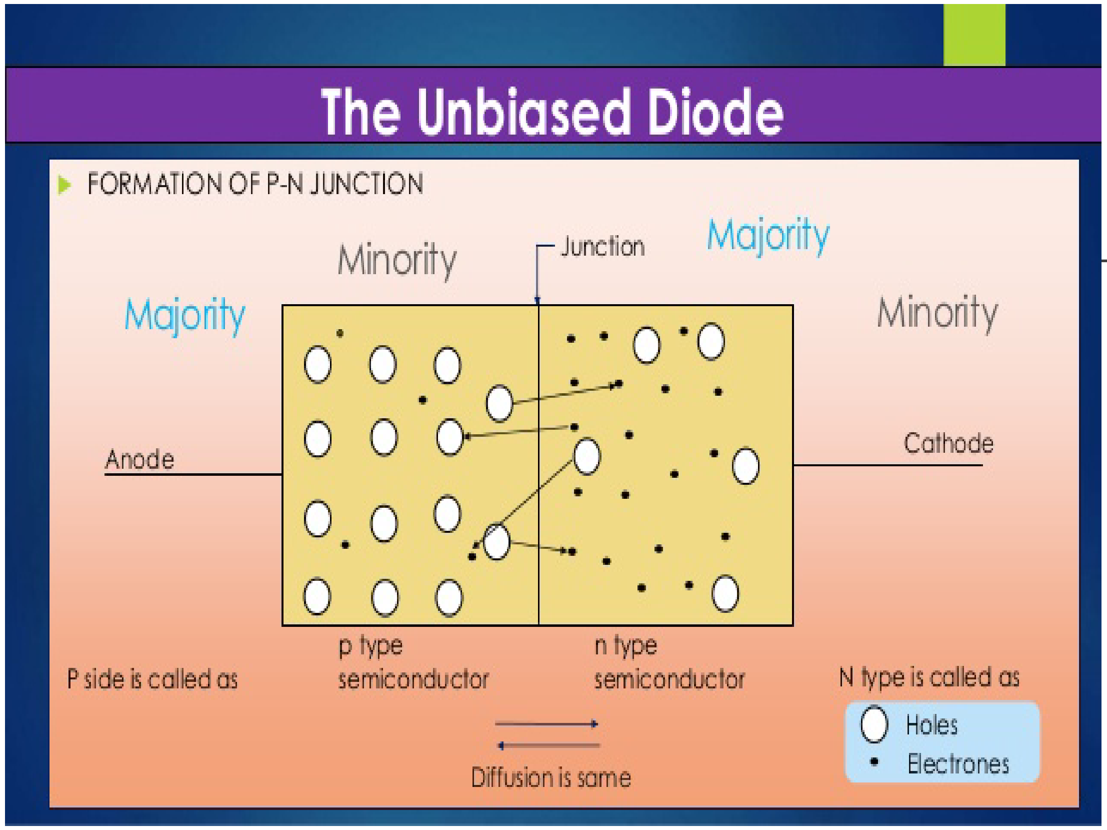
- Power Supplies – Block diagram, Rectifiers, Reservoir and smoothing circuits, Full-wave rectifiers, Bi-phase rectifier circuits, Bridge rectifier circuits, Voltage regulators, Output resistance and voltage regulation, Voltage multipliers
- Amplifiers – Types of amplifiers, Gain, Input and output resistance, Frequency response, Bandwidth, Phase shift, Negative feedback, Multi-stage amplifiers.
- Operational amplifiers - Operational amplifier parameters, Operational amplifier characteristics, Operational amplifier configurations, Operational amplifier circuits.
- Oscillators – Positive feedback, Conditions for oscillation, Ladder network oscillator, Wein bridge oscillator, Multivibrators, Single-stage astable oscillator, Crystal controlled oscillators.
- Self-study topics: BJT amplifier types, comparison of BJT & FET.

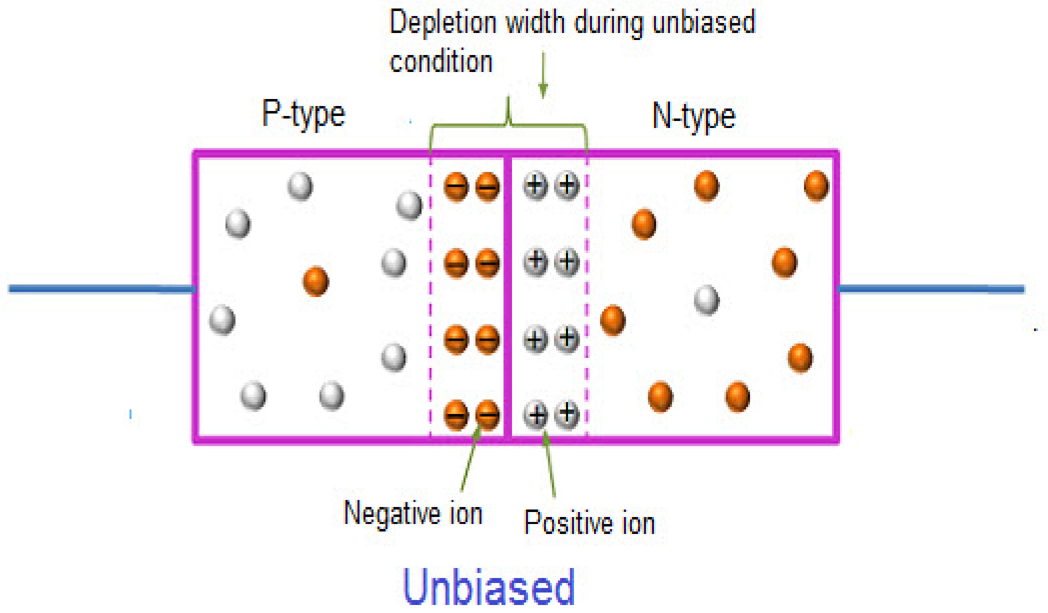
Semiconductor diode



- Two-terminal unilateral device which allows the flow of current in only one direction
- Anode and cathode are the two terminals
- Diode offers low resistance hence permits current flow from Anode to Cathode
- It offers high resistance or restricts the flow of current from Cathode to Anode
- It can be biased (applying voltage across terminals of diode) in two ways: Forward bias and Reverse bias
- Diode is a pn junction which permits current flow when forward biased and blocks current when reverse biased

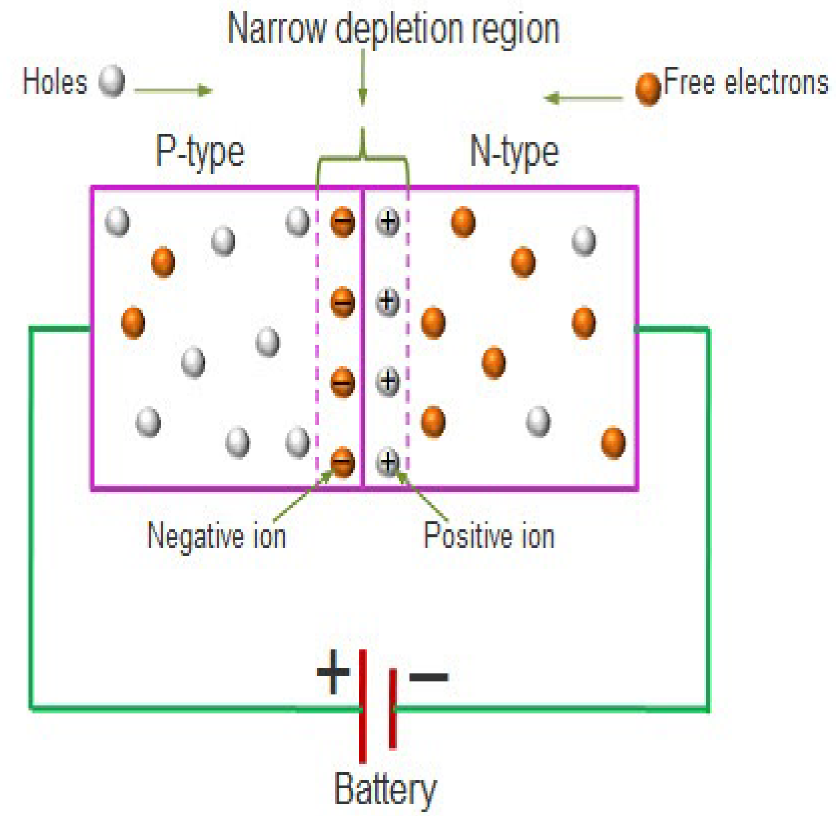
Unbiased Diode





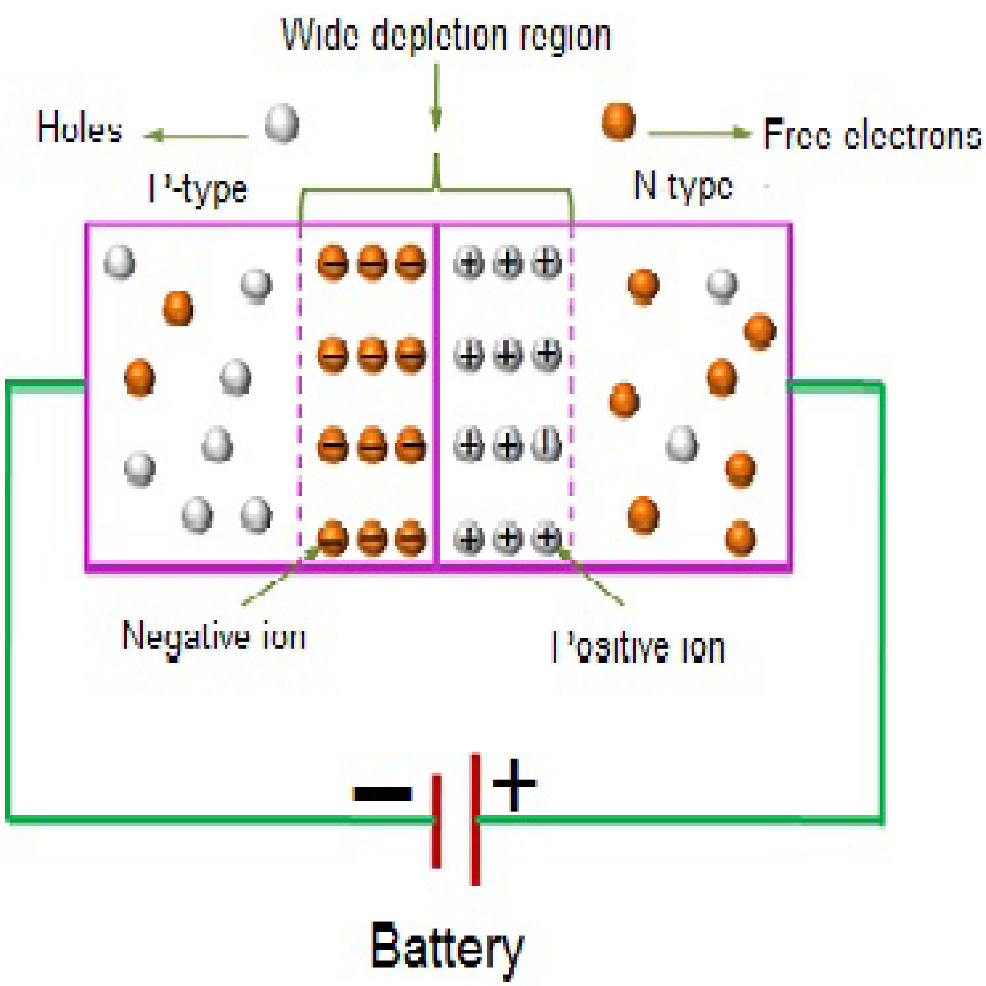
- No voltage applied across the junction
- Majority holes on p side start diffusing into n side
- Majority free electrons on n side start diffusing into p side
- Positive immobile ions are formed on n side and negative ions on p side near the junction, this is called depletion region
- In equilibrium condition, depletion region widens up to a point where no further electrons or holes can cross the junction. This acts as a barrier.
- Potential difference across depletion region is called barrier potential/junction potential/built-in voltage/cut-in potential
- Net current in unbiased diode is Zero.

Forward biased diode



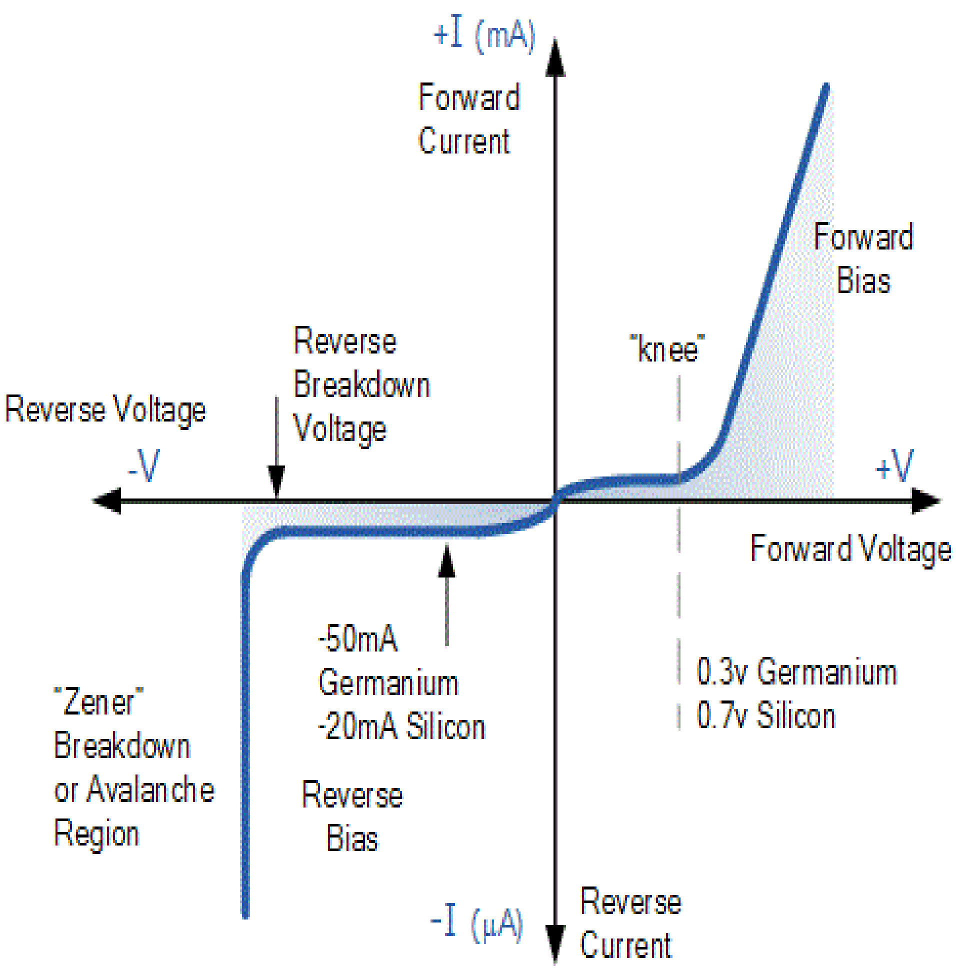
- P region is connected to positive and n region is connected to negative of dc supply
- Negative of the battery pushes free electrons across the depletion region, provided the applied voltage exceeds barrier voltage. Similarly, negative of the battery pushes holes against barrier from p to n region
- Barrier voltage for Si diode is 0.7V and Ge diode is 0.3V.
- Due to this width of the depletion region reduces and barrier potential also reduces
- Majority carriers cross the junction
- Hence current starts flowing from p to n side (Anode to cathode terminal)-Forward current

Reverse biased diode



- P region is connected to negative and n region to positive of the dc voltage
- Negative of the battery attracts holes in p region and positive of the battery attracts electrons in n region
- Majority charge carriers move away from the junction
- Depletion region widens and barrier potential increases
- Resistance of diode is high
- Due to increased barrier potential, free electrons on p side are attracted towards positive while holes towards negative of the battery
- There is a very small reverse current due to the flow of minority carriers
- Reverse current is constant though reverse voltage is increased upto a limit. It is called reverse saturation current.
- Minority charge carriers are thermally generated hence this current is temperature dependant
- Reverse saturation current is in the order of micro amperes for Ge and few nano amperes for Si diodes

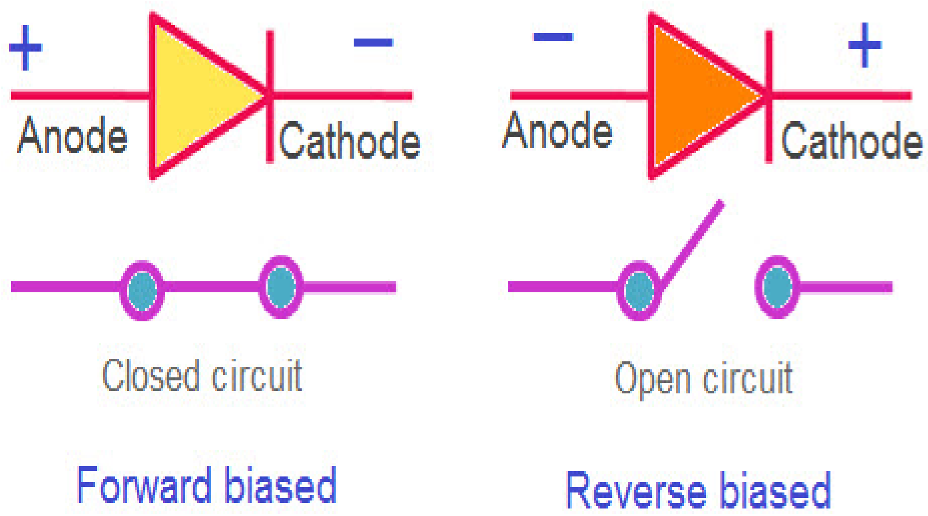
Current voltage or I-V characteristics of diode



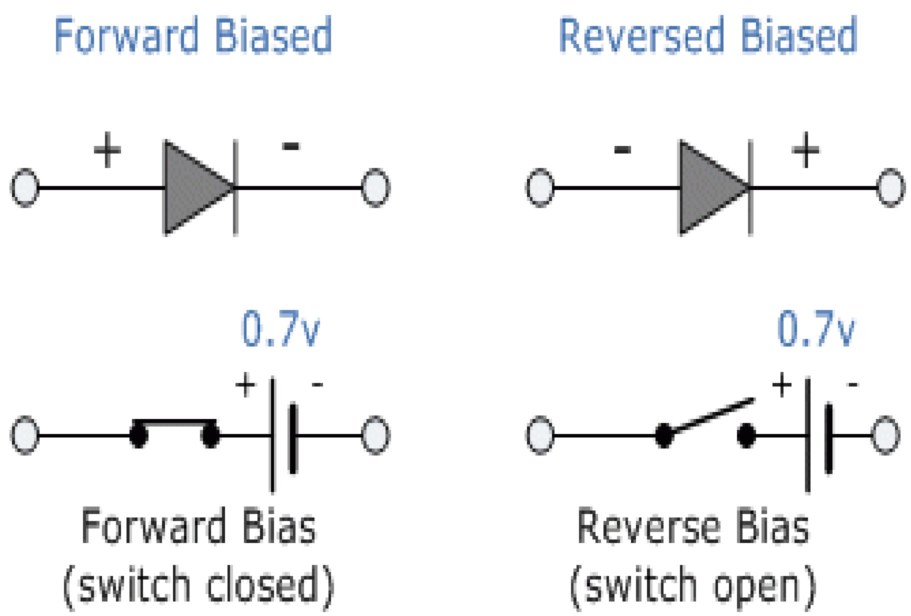
- First quadrant indicates the behaviour of diode when forward biased
- Current is nearly zero when forward voltage is less than knee or barrier voltage
- As forward voltage exceeds barrier voltage, current increases exponentially
- Third quadrant indicates the characteristics of reverse biased diode
- As the reverse voltage is increased, reverse current increases initially but after a small voltage becomes constant equal to reverse saturation current. Though reverse voltage is increased the reverse current remains constant.
- At reverse breakdown voltage, breakdown of diode occurs and current increases sharply damaging the diode.

Diode approximations

Ideal diode model
model

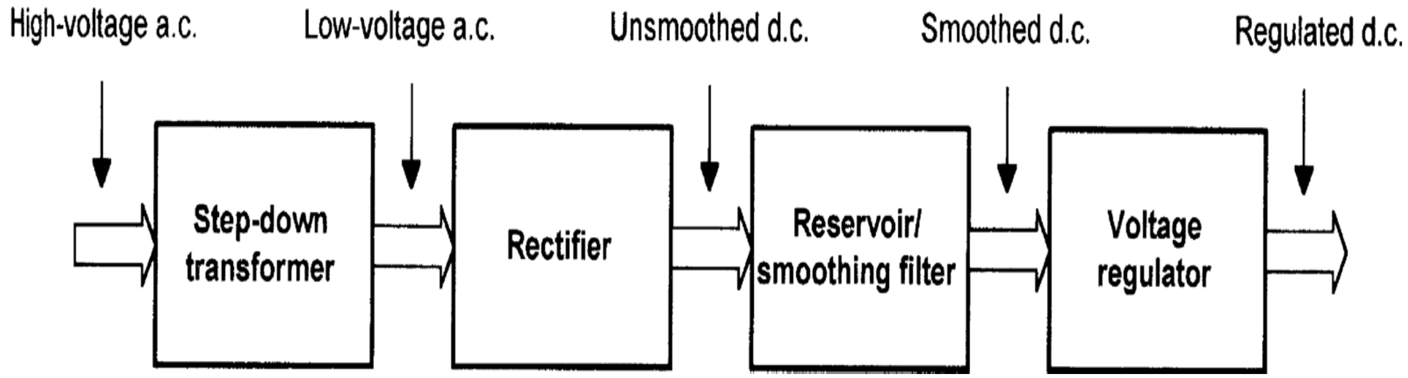


Constant voltage drop



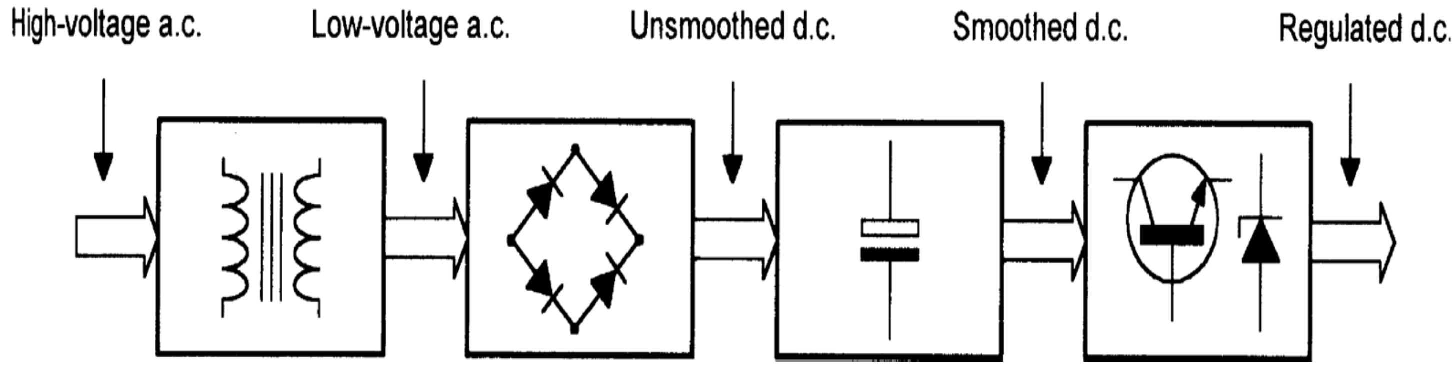
DC power supply

- A step-down transformer of appropriate turns ratio is used to convert high voltage from the mains to a low voltage.
- The a.c. output from the transformer secondary is then rectified using conventional silicon rectifier diodes to produce an unsmoothed (sometimes referred to as pulsating d.c.) output.
- The output is 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.



DC power supply

- The iron-cored step-down transformer feeds a rectifier arrangement (often based on a bridge circuit).
- The output of the rectifier is then applied to a high-value reservoir capacitor. The capacitor helps to smooth out the voltage pulses produced by the rectifier.
- A stabilizing circuit (often based on a series transistor regulator and a zener diode voltage reference) provides a constant output voltage.

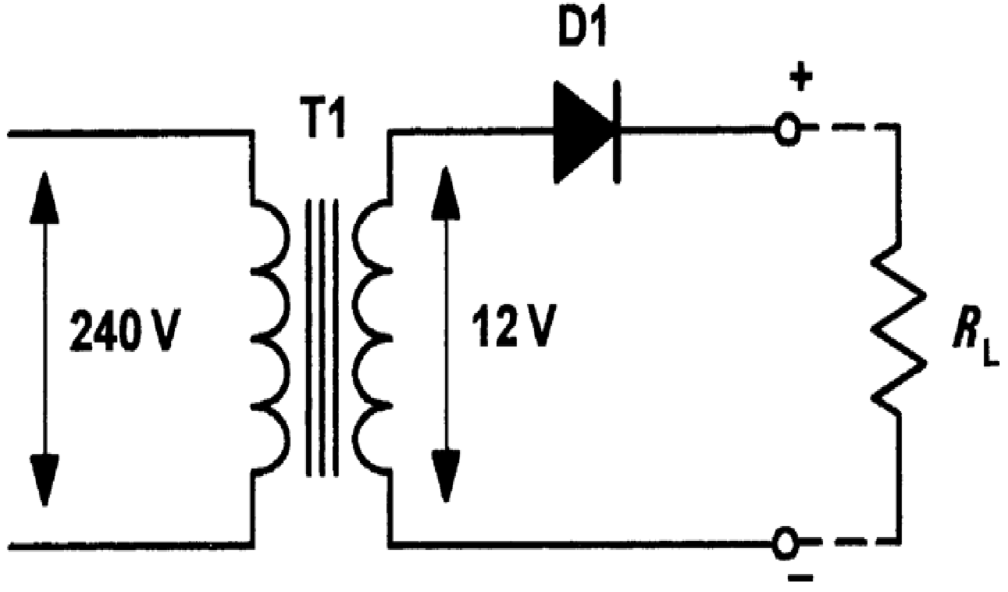


Rectifiers

- Semiconductor diodes are commonly used to convert alternating current (a.c.) to direct current (d.c), in which case they are referred to as rectifiers.
- Types- Half-wave rectifier, Full-wave rectifier, Bridge rectifier
- Half-wave rectifier uses single diode and operates on only either positive or negative half-cycles of the supply
- Full-wave rectifier uses two diodes with centre tap transformer and operates in both positive and negative half cycles
- Bridge rectifier uses four diodes and operates in both positive and negative half cycles

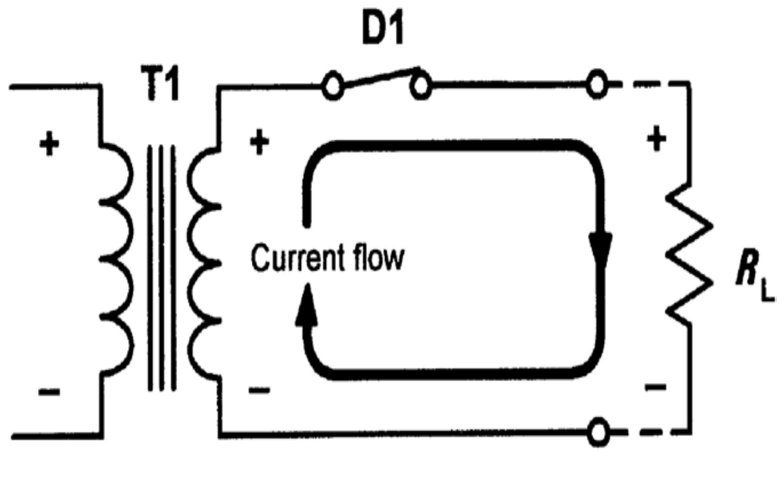
Half-wave rectifier

- 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. (the turns ratio of T1 will thus be 240/12 or 20:1).
- D1 will be forward biased during each positive half-cycle (relative to common) and will effectively behave like a closed switch.
- D1 will be reverse biased during each negative half-cycle and will effectively behave like a open switch.

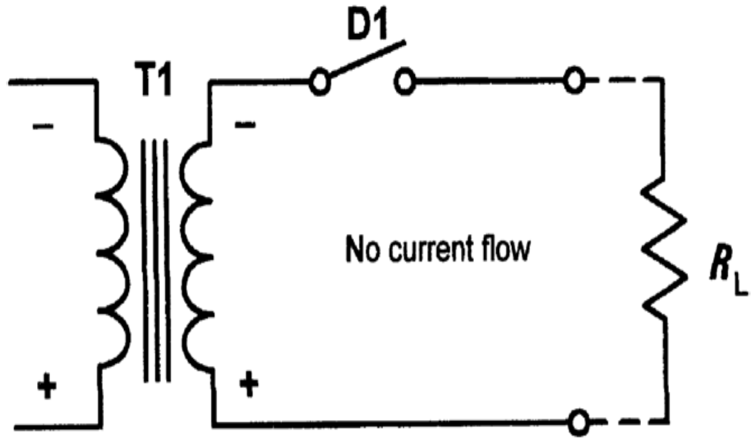


Half-wave rectifier- Working

- The switching action of D1 results in a pulsating output voltage which is developed across the load resistor (RL).
- Mains supply and output developed across RL both have same frequency 50 Hz.
- During the positive half-cycle, the diode will drop the 0.6 V to 0.7 V forward threshold voltage normally associated with silicon diodes.
- However, during the negative half-cycle the peak a.c. voltage will be dropped across D1 when it is reverse biased. This is an important consideration when selecting a diode for a particular application.



(a)



(b)

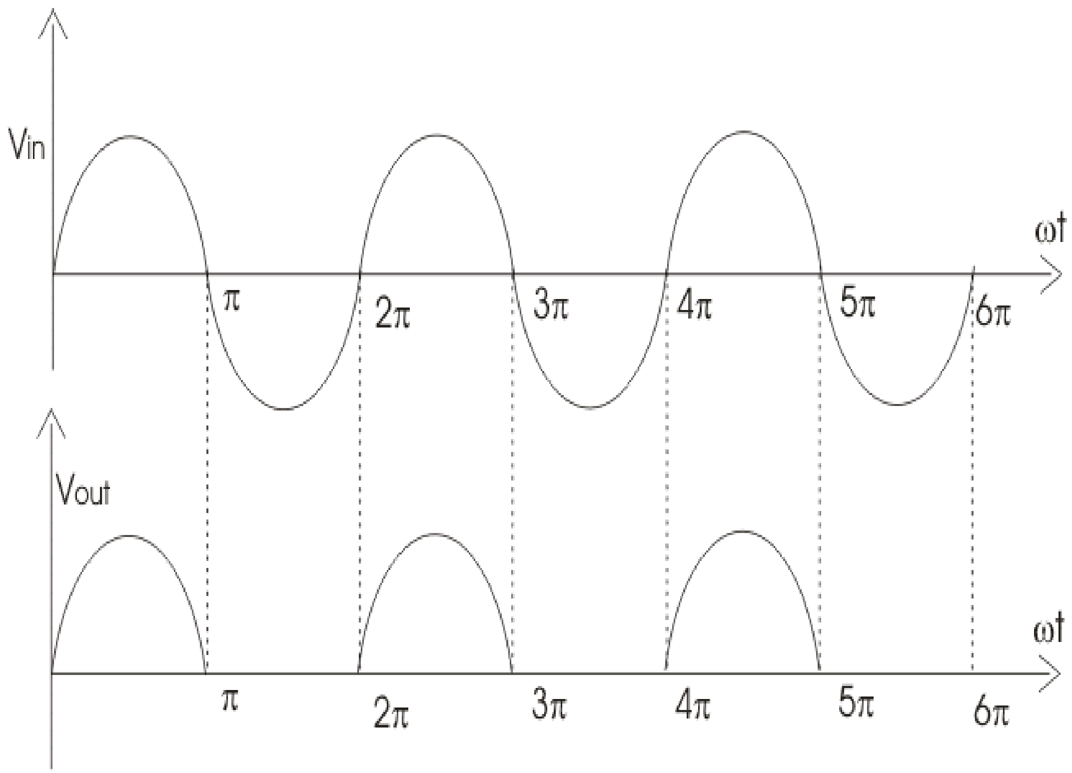
Half-wave rectifier- Working

- Assuming that the secondary of T1 provides 12 V r.m.s., the peak voltage output from the transformer's secondary winding will be given by:

$$V_{pk} = 1.414 \times V_{r.m.s.} = 1.414 \times 12\ V = 16.97\ V$$

- The peak voltage a… negative half-cycles are blocked by D1 and thus only the positive half-cycle appear across RL.
- Actual peak voltage across RL will be the 17 V positive peak being supplied from the secondary on T1, minus the 0.7 V forward threshold voltage dropped by D1. Positive half-cycle pulses having a peak amplitude of 16.3 V will appear across RL.

Half-wave rectifier- Waveforms



Problem 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.

Ans:

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

$$V_S = V_P / 44 = 220 / 44 = 5 \text{ V}$$

The peak voltage developed after rectification will be given by:

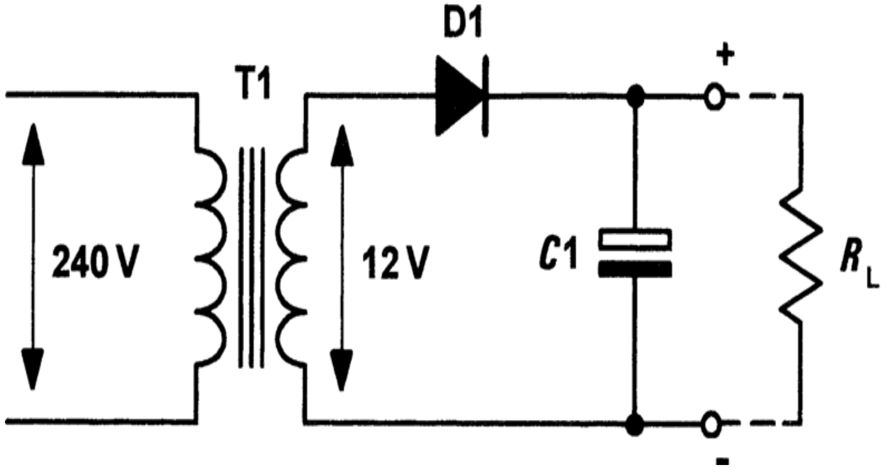
$$V_{PK} = 1.414 \times 5 \text{ V} = 7.07 \text{ V}$$

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

$$V_L = 7.07 \text{ V} - 0.6 \text{ V} = 6.47 \text{ V}$$

Reservoir and smoothing circuits

- Improvement in Half-wave rectifier circuit is possible by adding the capacitor, C1, 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 RL.
- Hence C1 charges to 16.3 V at the peak of the positive half-cycle. Because C1 and RL are in parallel, the voltage across RL 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).

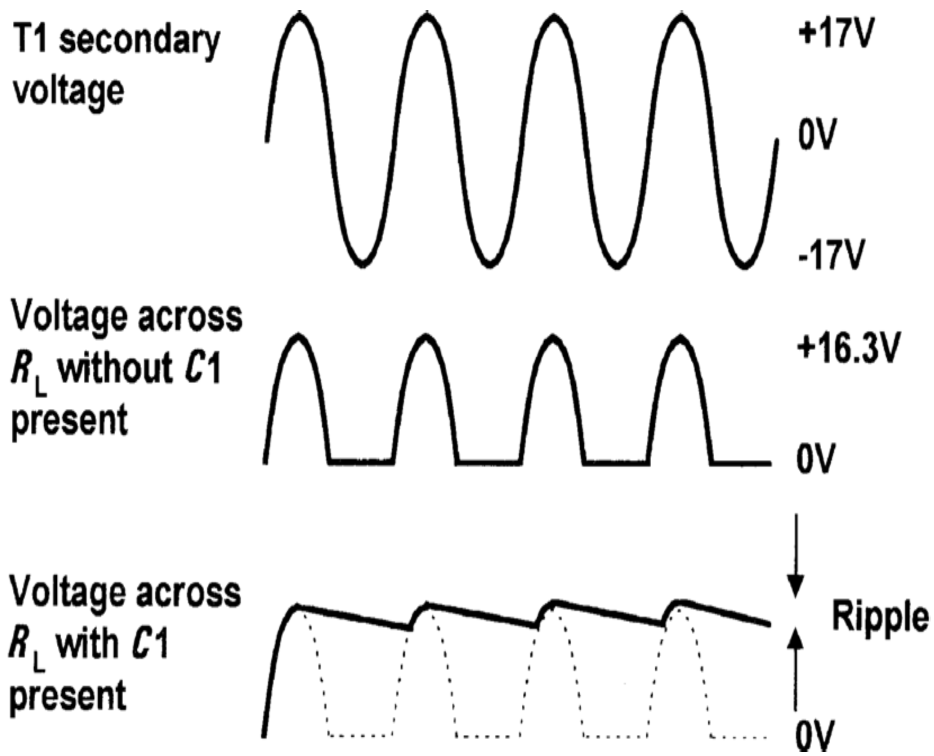


Half-wave rectifier with capacitor filter

- 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, RL.
- In practice, RL 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 RL.

Half-wave rectifier with capacitor filter

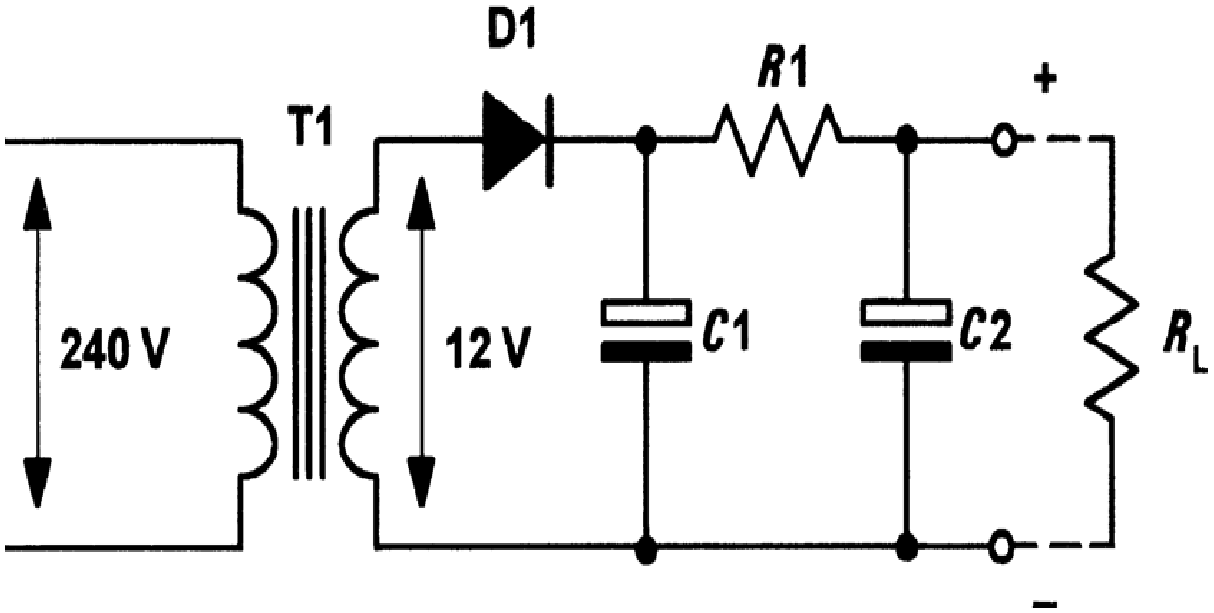
- C1 is referred to as a reservoir capacitor. It stores charge during the positive half-cycles of secondary voltage and releases it during the negative half-cycles.
- C1 will discharge by a small amount during the negative half-cycle periods from the transformer secondary.
- Small variation in dc output voltage is ripple
- Since ripple is undesirable we must take additional precautions to reduce it. One obvious method of reducing the amplitude of the ripple is that of simply increasing the discharge time constant.
- Discharge time constant can be increased by increasing the value of C1 or by increasing the resistance value of RL. Usually RL cant be changed.
- Increasing the value of C1 is a more practical alternative and very large capacitor values (often in excess of 4,700 µF) are typical.



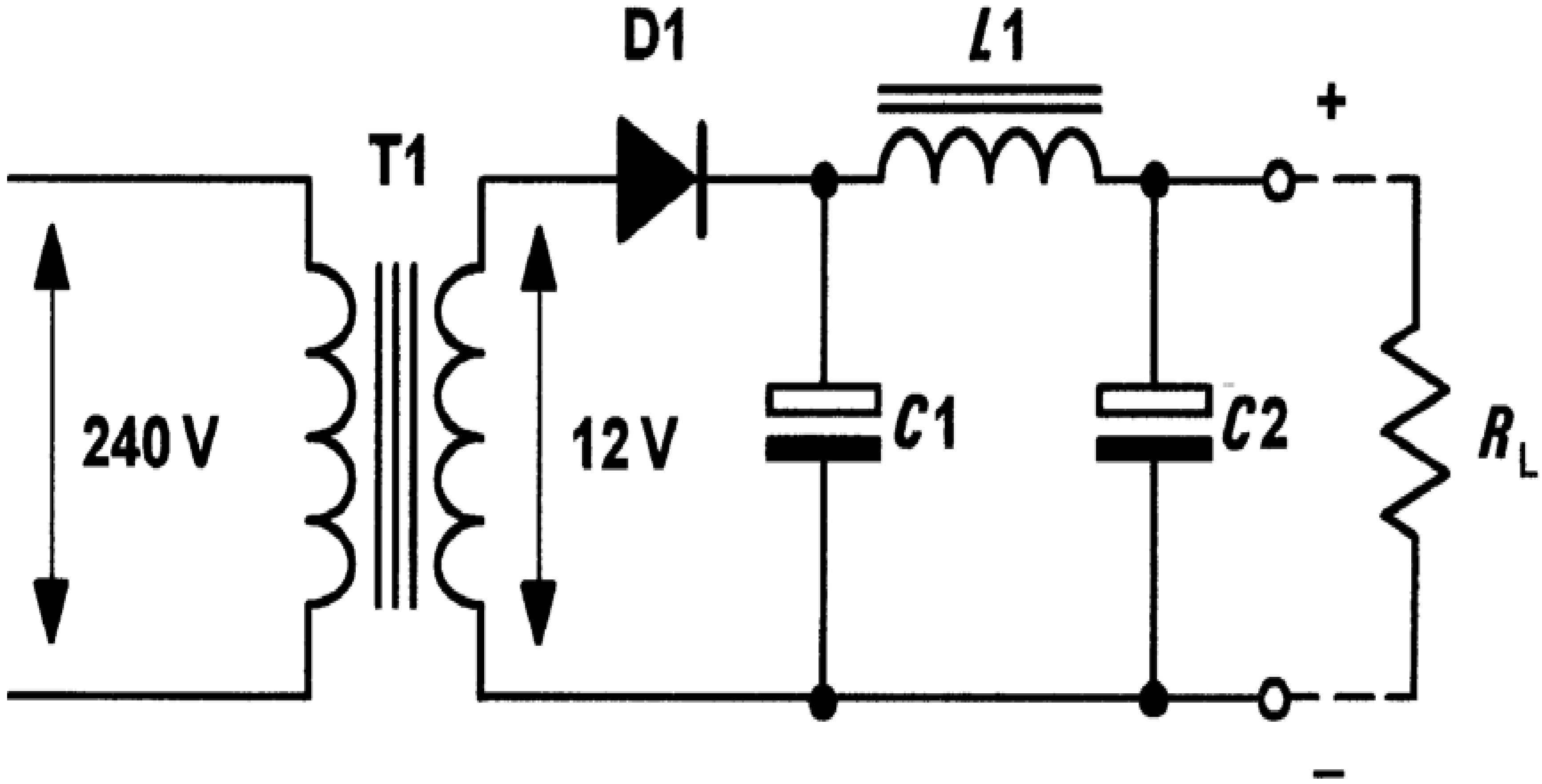
Refinement to the circuit to reduce ripple (use of R-C smoothing filter)

- 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)
- The amount of ripple is reduced by an approximate factor equal to:

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



Half-wave rectifier circuit with L – C smoothing filter



Problem 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.

Ans:

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

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

The amount of ripple at the output of the circuit (i.e. appearing across *C*1) 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:

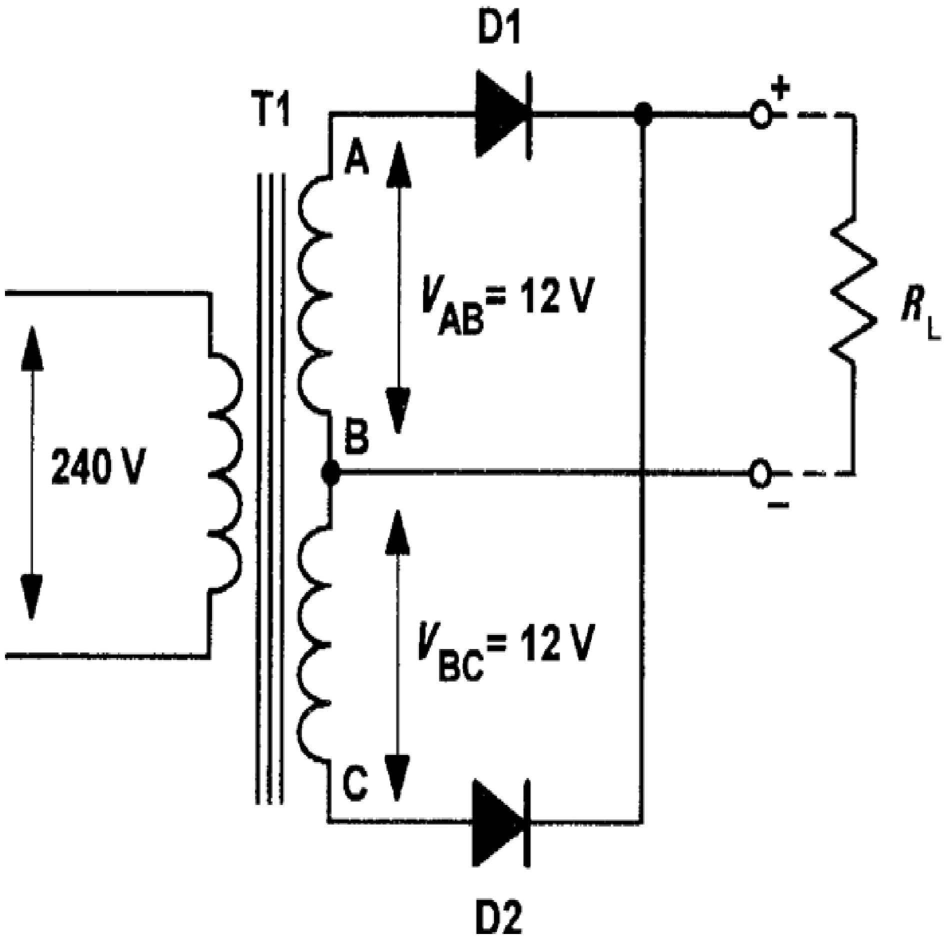
$$V = 0.032\ \text{V} = 32\ \text{mV}$$

Full-wave rectifiers

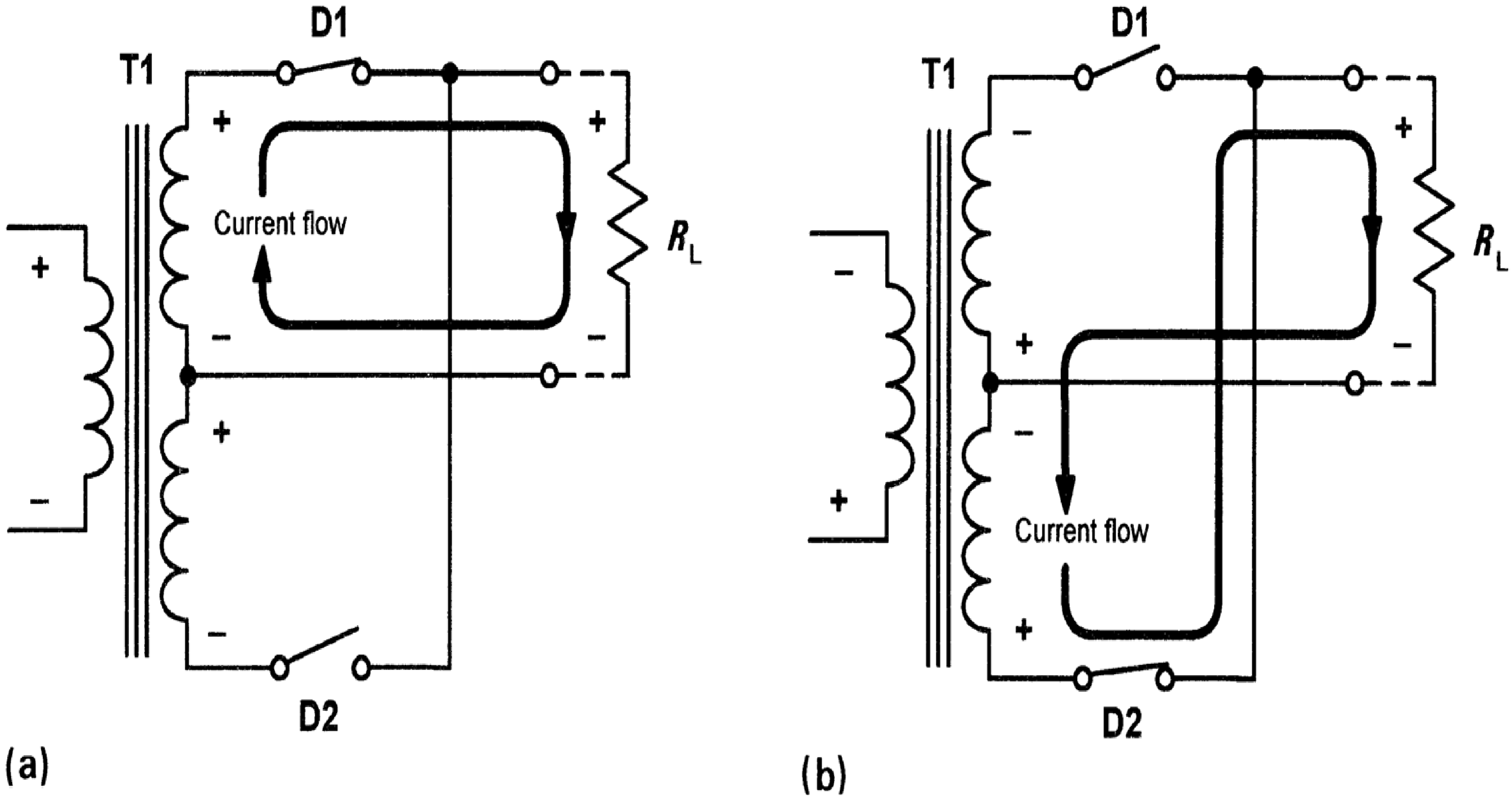
- A better rectifier arrangement would make use of both positive and negative half-cycles.
- Improvement over half-wave rectifiers
- They are not only more efficient but are significantly less demanding in terms of the reservoir and smoothing components.
- Two types: phase type and the bridge rectifier type.

Bi-phase rectifier circuits

- 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 while D2 will not allow conduction.
- 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 while D1 will not allow conduction.

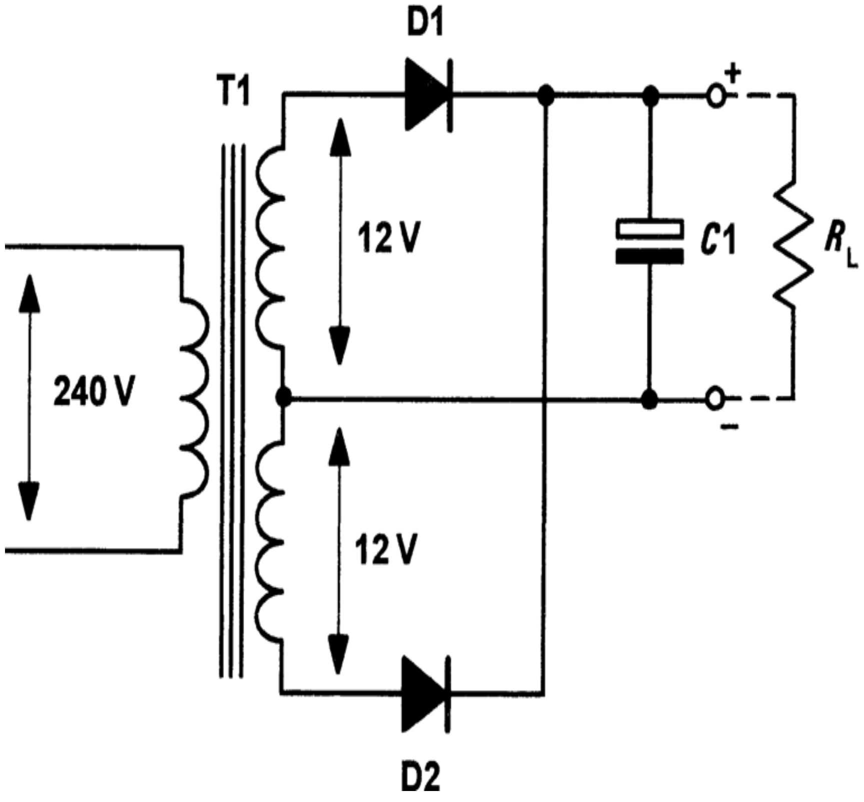


Equivalent circuits during positive and negative half-cycle



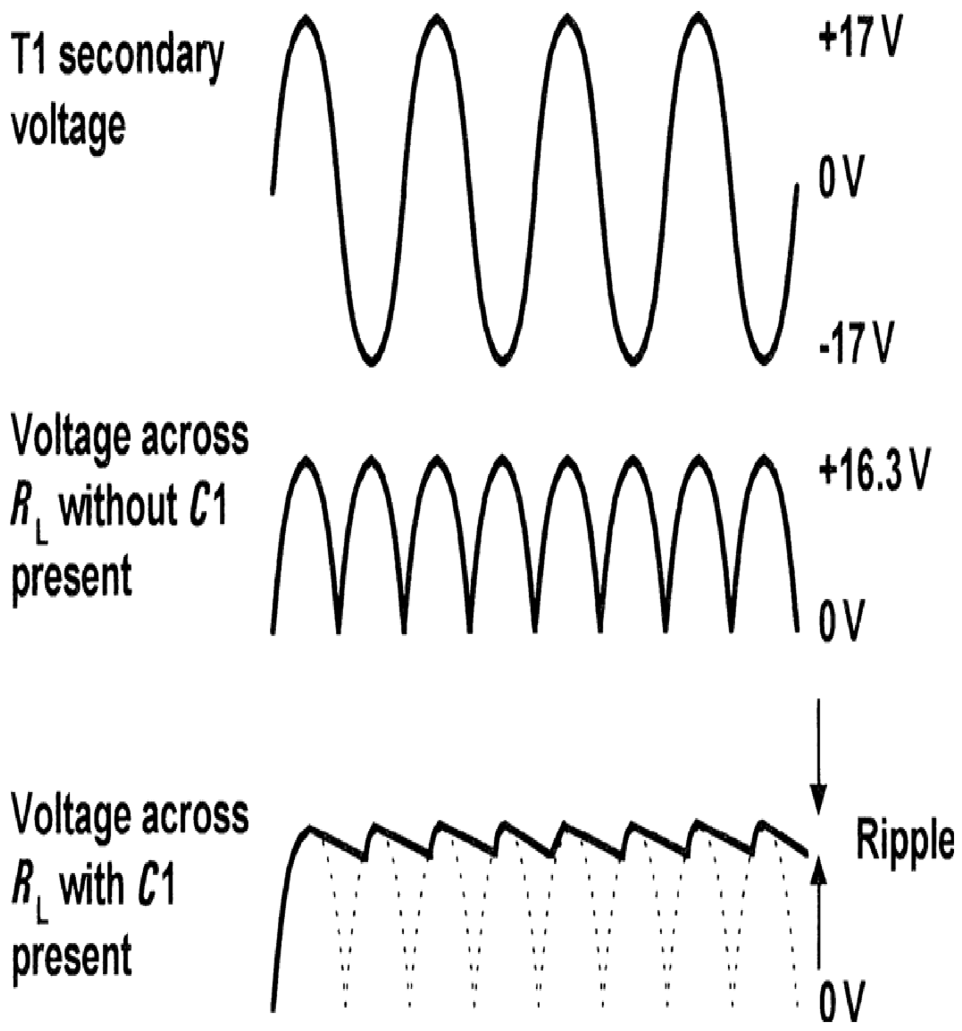
Bi-phase rectifier circuits with capacitor filter

- The current is routed through the load in the same direction on successive half-cycles.
- Pulsating output voltage being developed across the load resistor (RL). Frequency of the output is 100 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.
- 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
- If C1 is added at the output, 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.



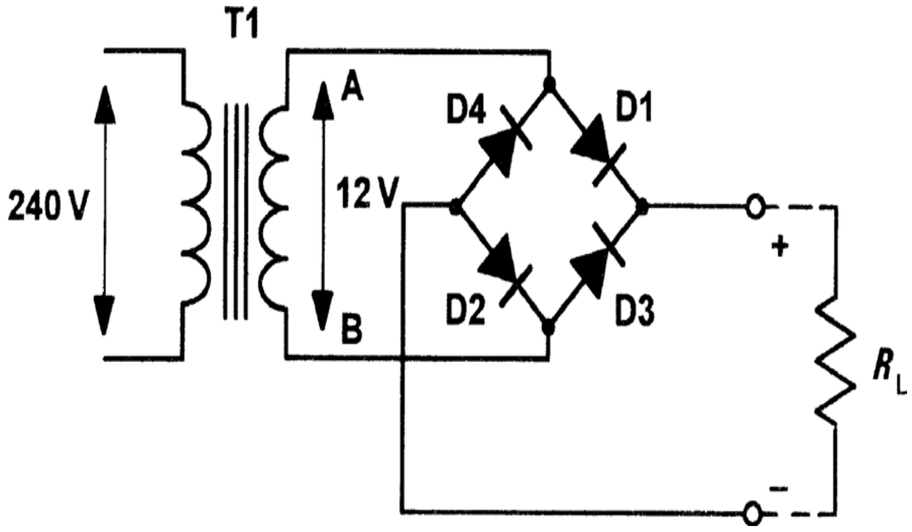
Bi-phase rectifier circuits-waveforms

- The time required for C1 to charge to the maximum (peak) level is determined by series resistance which comprises of 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, RL which is large.
- C1 takes an appreciable time to discharge.
- During this time, D1 and D2 will be reverse biased and held in a non-conducting state, thus only discharge path for C1 is through RL.



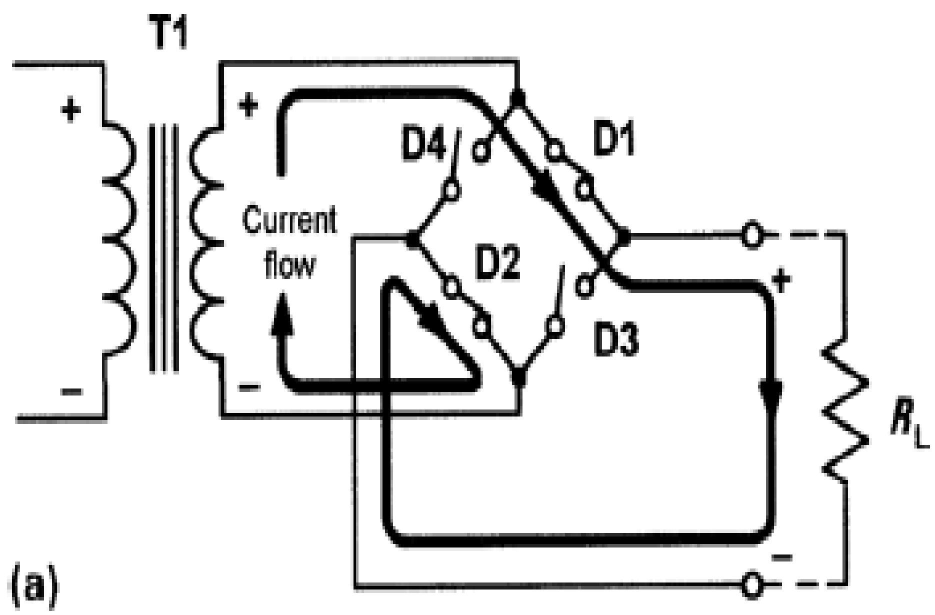
Bridge rectifier circuits

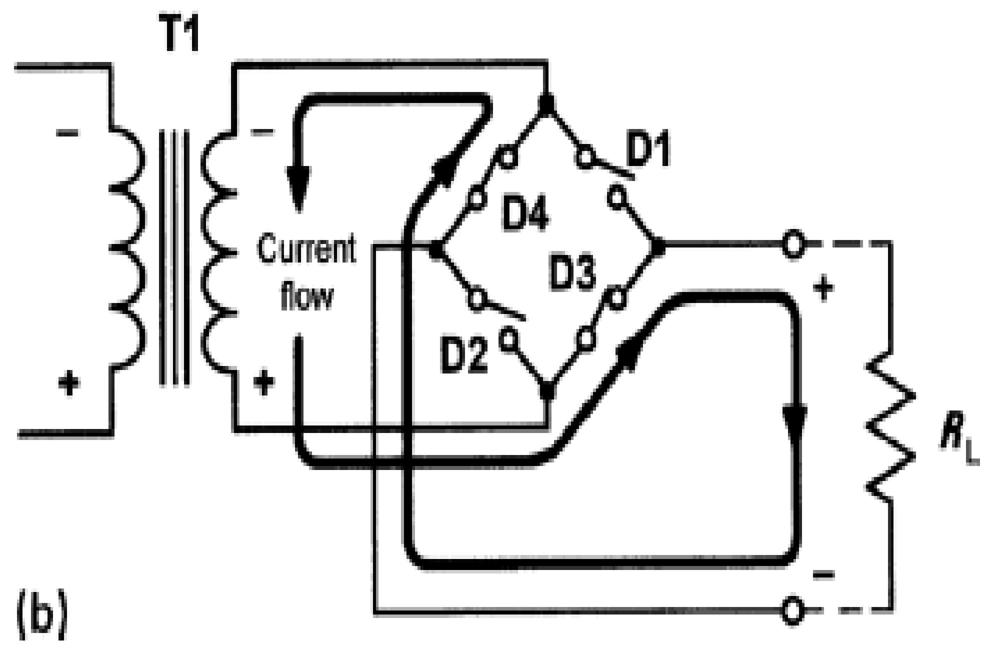
- This arrangement avoids the need to have two separate secondary windings. It uses 4 diodes.
- Mains voltage (240 V) is applied to the primary of a step-down transformer (T1). The secondary winding provides 12 V r.m.s. (approximately 17 V peak) and has a turns ratio of 20:1
- On positive half-cycles, 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.



Equivalent circuits during positive and negative half cycles

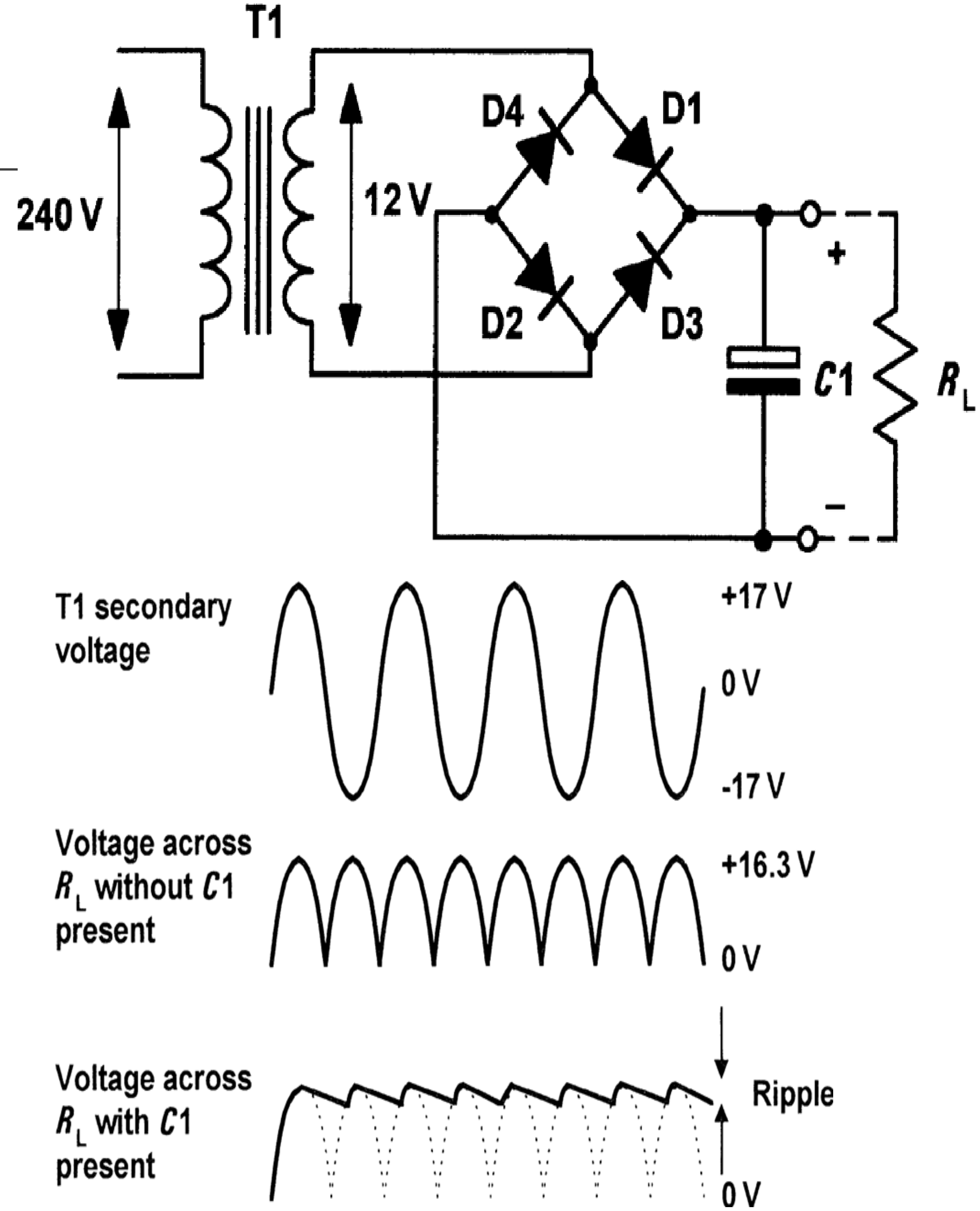
- Once again, the result is that current is routed through the load in the same direction on successive half-cycles.
- Once again, the peak output voltage is approximately 16.3 V (i.e. 17 V less the 0.7 V forward threshold voltage).





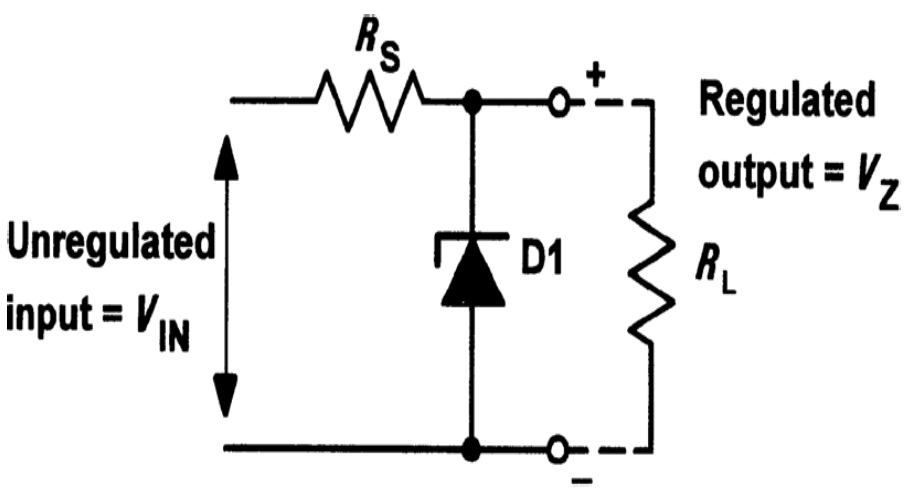
Bridge rectifier circuits with reservoir capacitor

- Reservoir capacitor (C1) can be added to maintain the output voltage when the diodes are not conducting.
- C1 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.
- 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



Voltage regulators

- Regulator circuit using Zener diode
- Rs is included to limit the zener current to a safe value when the load is disconnected
- When a load (RL) is connected, the zener current (IZ) 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 VZ.



Equations

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

where VIN is the unregulated input voltage

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

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:

$$R_S \text{ min.} = \frac{V_{IN} - V_Z}{I_Z} = \frac{V_{IN} - V_Z}{\left(\frac{P_Z \text{ max.}}{V_Z} \right)} = \frac{(V_{IN} - V_Z) \times V_Z}{P_Z \text{ max.}}$$

Thus:

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

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

Problem 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.

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

$$R_S \text{ min.} = \frac{V_{IN} V_Z - V_Z^{\,2}}{P_Z \text{ max.}} \qquad R_S \text{ min.} = \frac{(9 \times 5) - 5^2}{0.5} = \frac{45 - 25}{0.5} = 40\ \Omega$$

Output resistance and voltage regulation

- In a perfect power supply, the output voltage would remain constant regardless of the current taken by the load, but in practice output voltage falls as the load current increases.
- Power supply has internal resistance (ideally this should be zero). This internal resistance appears at the output of the supply.

$$R_{out} = \frac{\text{change in output voltage}}{\text{change in output current}} = \frac{\Delta V_{out}}{\Delta I_{out}}$$

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

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

- Ideally, the value of regulation should be very small. Simple shunt zener diode regulators 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.

Problem 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.

Ans:

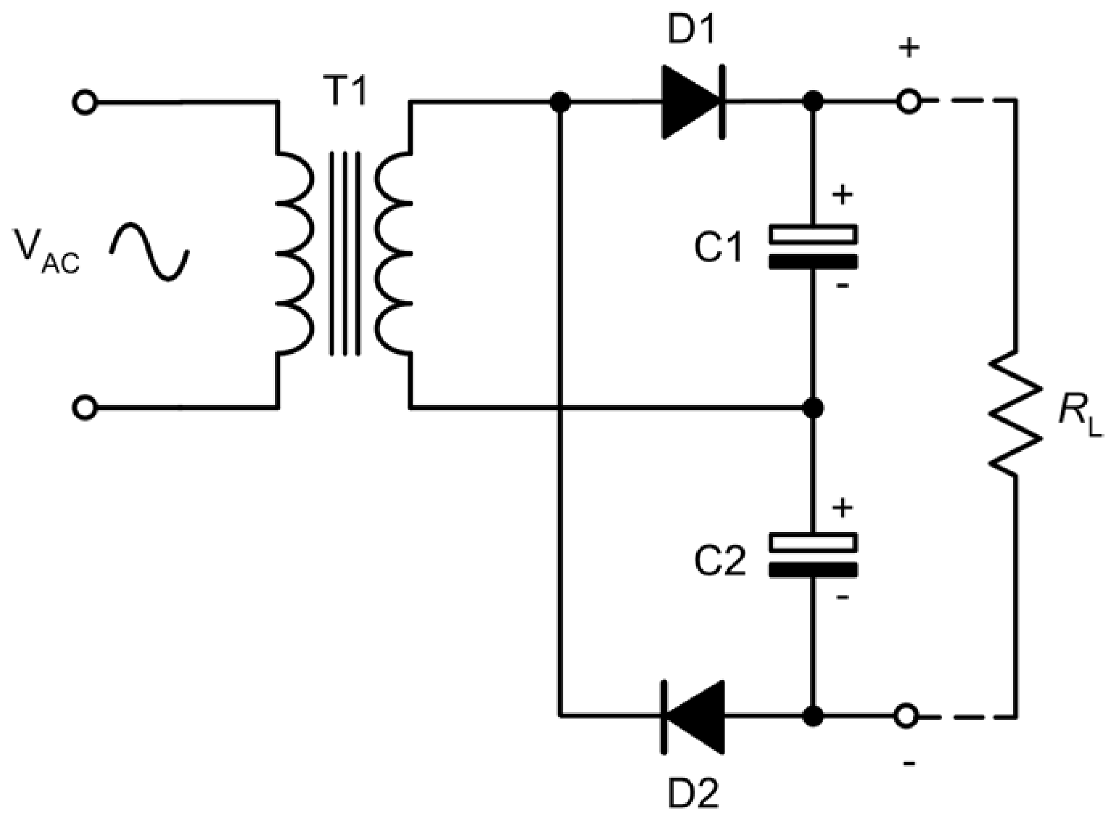
$$R_{out} = \frac{\text{change in output voltage}}{\text{change in output current}} = \frac{12 - 11.5}{2 - 0} = 0.25\ \Omega$$

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

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

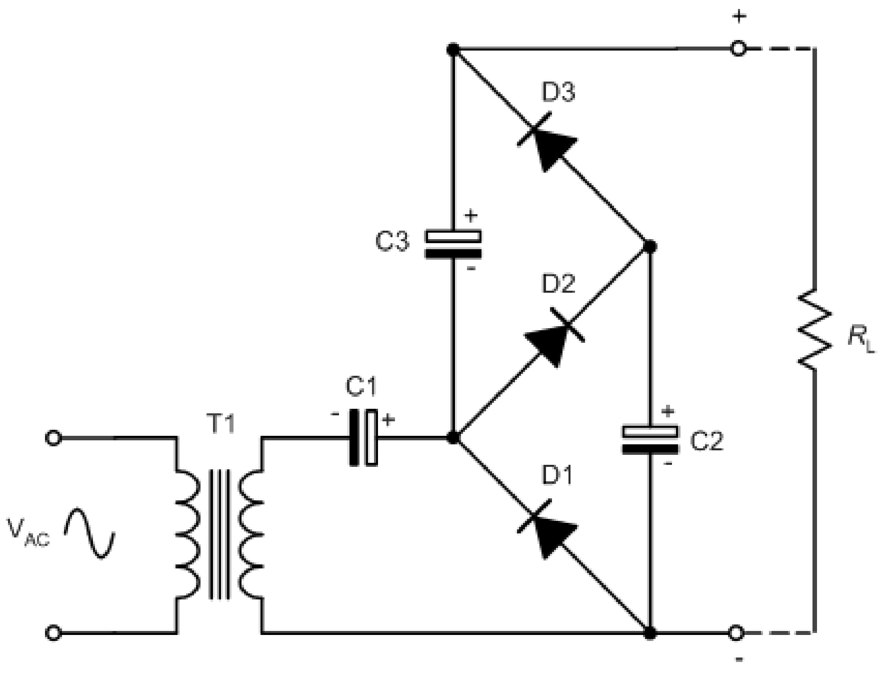
Voltage multipliers: Voltage doubler

- Increasing the output of simple half-wave rectifier
- 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.



Voltage tripler

- C1 charges to the positive peak secondary voltage, while C2 and C3 charge to twice the positive peak secondary voltage.
- 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.
- Circuit can be extended to provide even higher voltages but the efficiency of the circuit becomes less
- High-order voltage multipliers of this type are only suitable for providing relatively small currents.



Amplifiers

- Amplifiers are electronic circuits that increase the strength of a signal (voltage/current/power)
- It uses electric power from a power supply to increase the amplitude of a signal applied to its input terminals, producing a proportionally greater amplitude signal at its output.
- The amount of amplification provided by an amplifier is measured by its gain: the ratio of output voltage, current, or power to input.
- An amplifier can either be a separate piece of equipment or an electrical circuit contained within another device.
- Amplification is fundamental to modern electronics, and amplifiers are widely used in almost all electronic equipment.

Types of amplifier

- 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.
- d.c. 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.
- 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).
- 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.
- Audio frequency amplifiers: operate in the band of frequencies that is normally associated with audio signals (e.g. 20 Hz to 20 kHz).
- Wideband amplifiers: capable of amplifying a very wide range of frequencies, typically from a few tens of hertz to several megahertz.

Types of amplifier

- 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). They are frequency selective. They are restricted to narrow band of frequencies.
- 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).

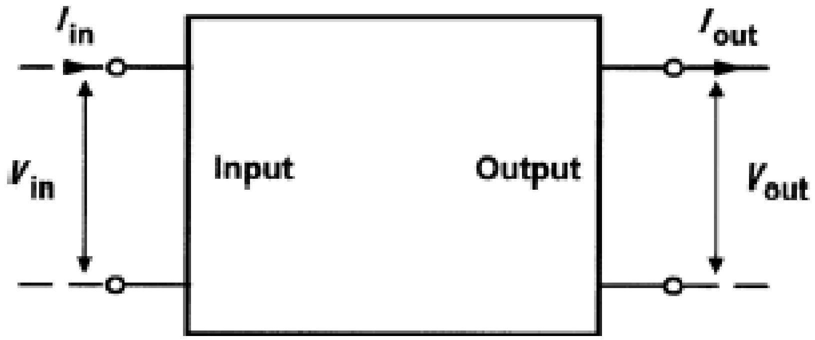
Gain

- It indicates amount of amplification
- Gain is simply the ratio of output voltage to input voltage, output current to input current, or output power to input power

Voltage gain, $A_v = \frac{V_{out}}{V_{in}}$

Current gain, $A_i = \frac{I_{out}}{I_{in}}$

Power gain, $A_p = \frac{P_{out}}{P_{in}}$



$$A_p = \frac{P_{out}}{P_{in}} = \frac{I_{out} \times V_{out}}{I_{in} \times V_{in}} = \frac{I_{out}}{I_{in}} \times \frac{V_{out}}{V_{in}} = A_i \times A_v$$

Problem 5

An amplifier produces an output voltage of 2 V for an input of 50 mV. If the input and output currents in this condition are, respectively, 4 mA and 200 mA, determine: (a) the voltage gain; (b) the current gain; (c) the power gain.

$$A_v = \frac{V_{out}}{V_{in}} = \frac{2\ \text{V}}{50\ \text{mV}} = 40$$

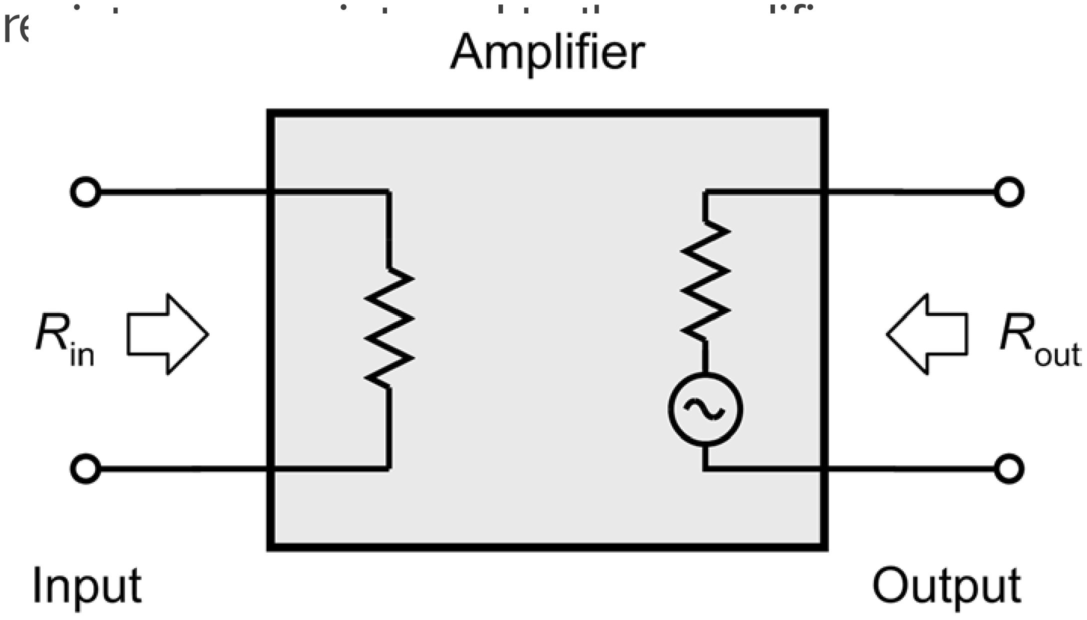
$$A_i = \frac{I_{out}}{I_{in}} = \frac{200\ \text{mA}}{4\ \text{mA}} = 50$$

$$A_p = \frac{I_{out} \times V_{out}}{I_{in} \times V_{in}} = \frac{200\ \text{mA} \times 2\ \text{V}}{4\ \text{mA} \times 50\ \text{mV}} = \frac{0.4\ \text{W}}{200\ \mu\text{W}} = 2{,}000$$

$$A_p = A_i \times A_v = 50 \times 40 = 2{,}000$$

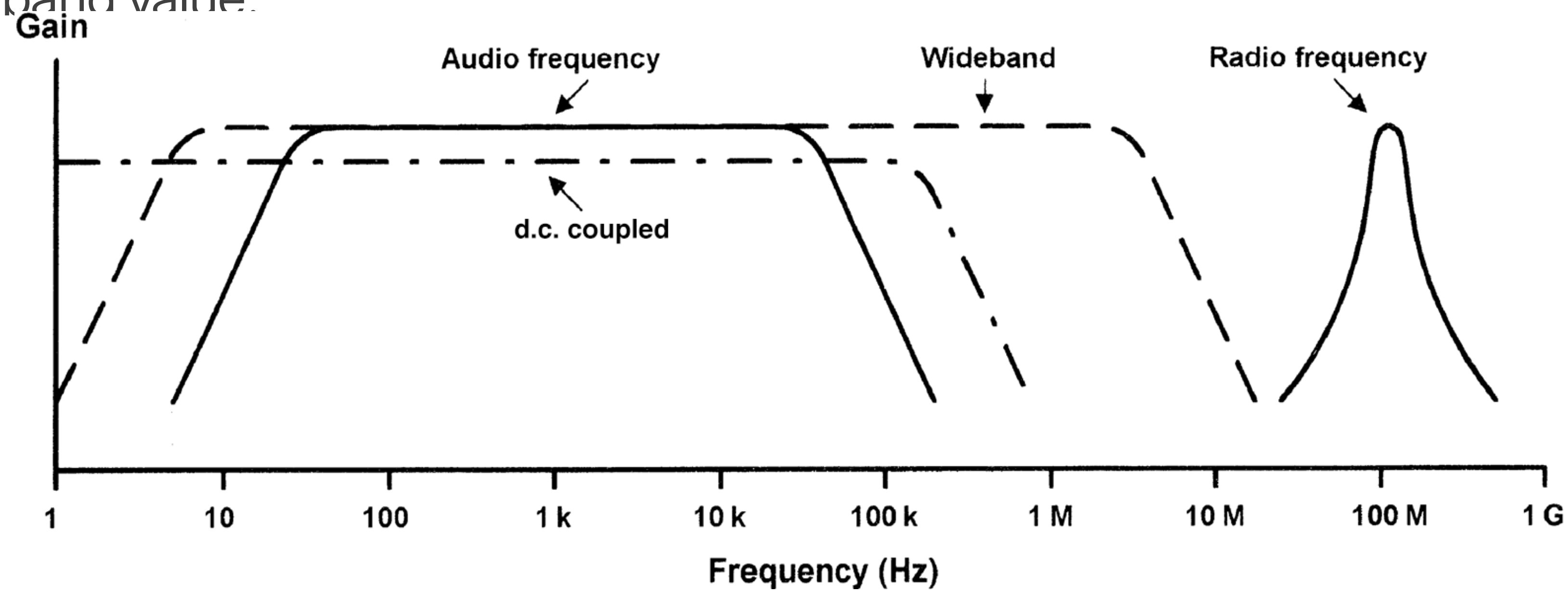
Input and output resistance

- Input resistance is the ratio of input voltage to input current and it is expressed in ohms. It is resistive in the mid band frequency band. In other cases it is complex quantity, then it is referred as input impedance considering the effect of capacitance in parallel with it.
- Output resistance is the ratio of open-circuit output voltage to short-circuit output current and is measured in ohms. In the presence of reactive component it is referred to as output impedance.
- Input and output re

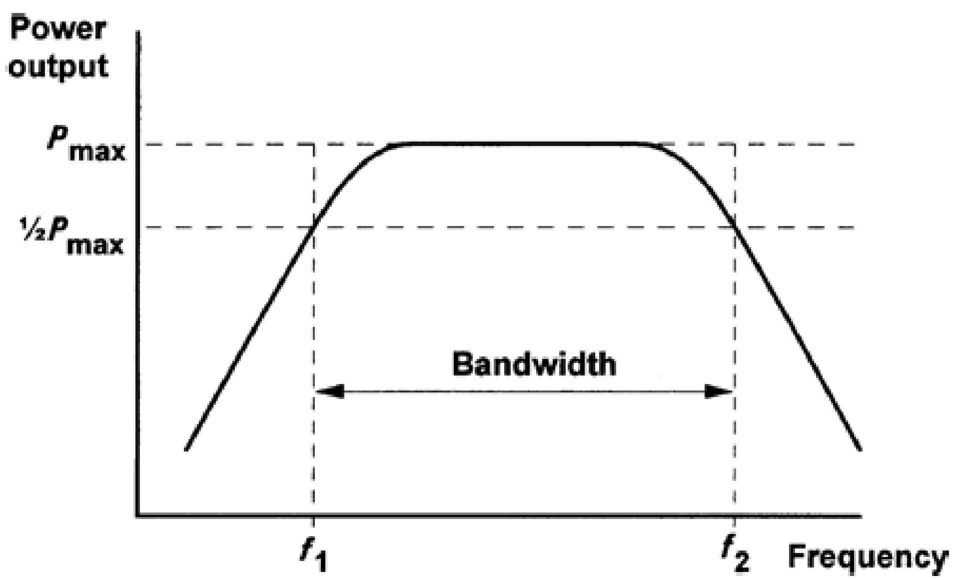


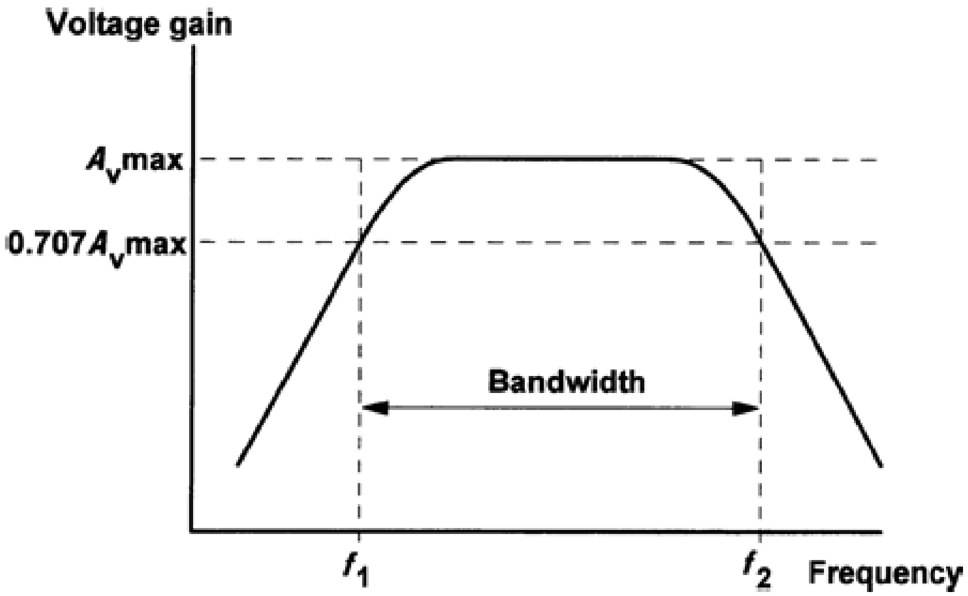
Frequency response

- Frequency response is a plot of gain of the amplifier versus frequency of the input source. It is mostly plotted on a logarithmic scale.
- 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.



Frequency response





Problem 6

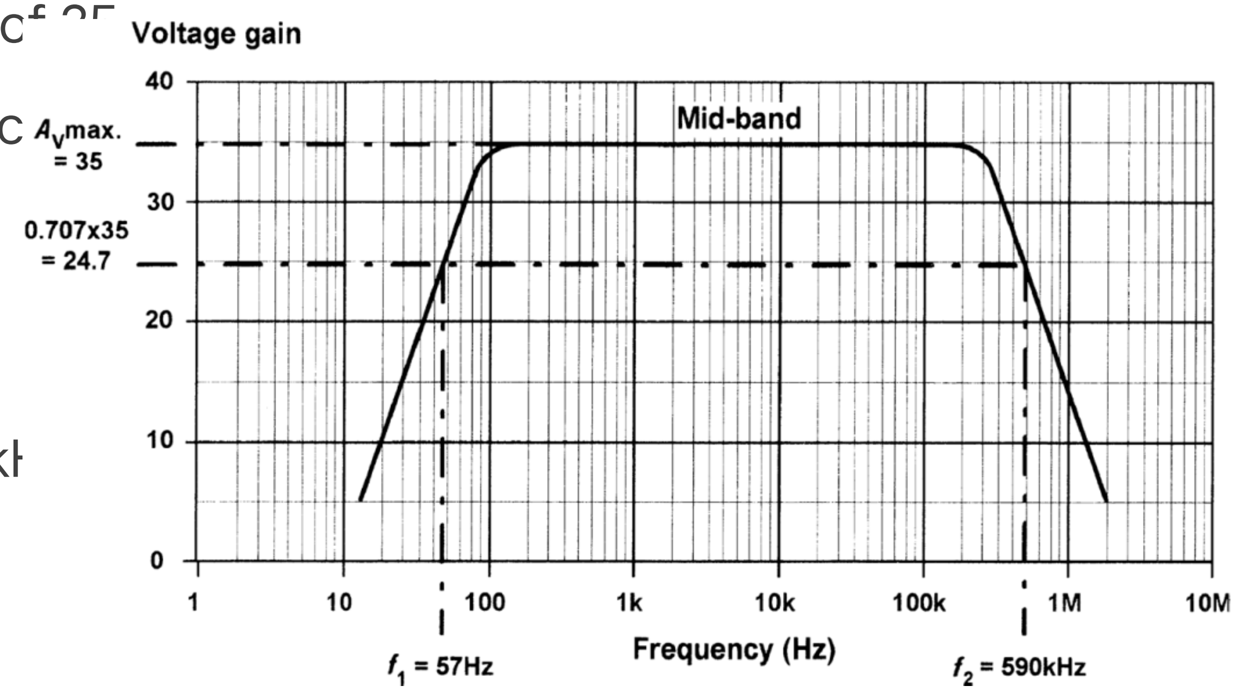
Determine the mid-band voltage gain and upper and lower cut-off frequencies for the amplifier whose frequency response is shown in Figure.

Ans: 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 frequenc can be calculated from:

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

This value of gain intercepts the frequency response graph at $f1$ = 57 Hz and $f2$ = 590 kH



Bandwidth

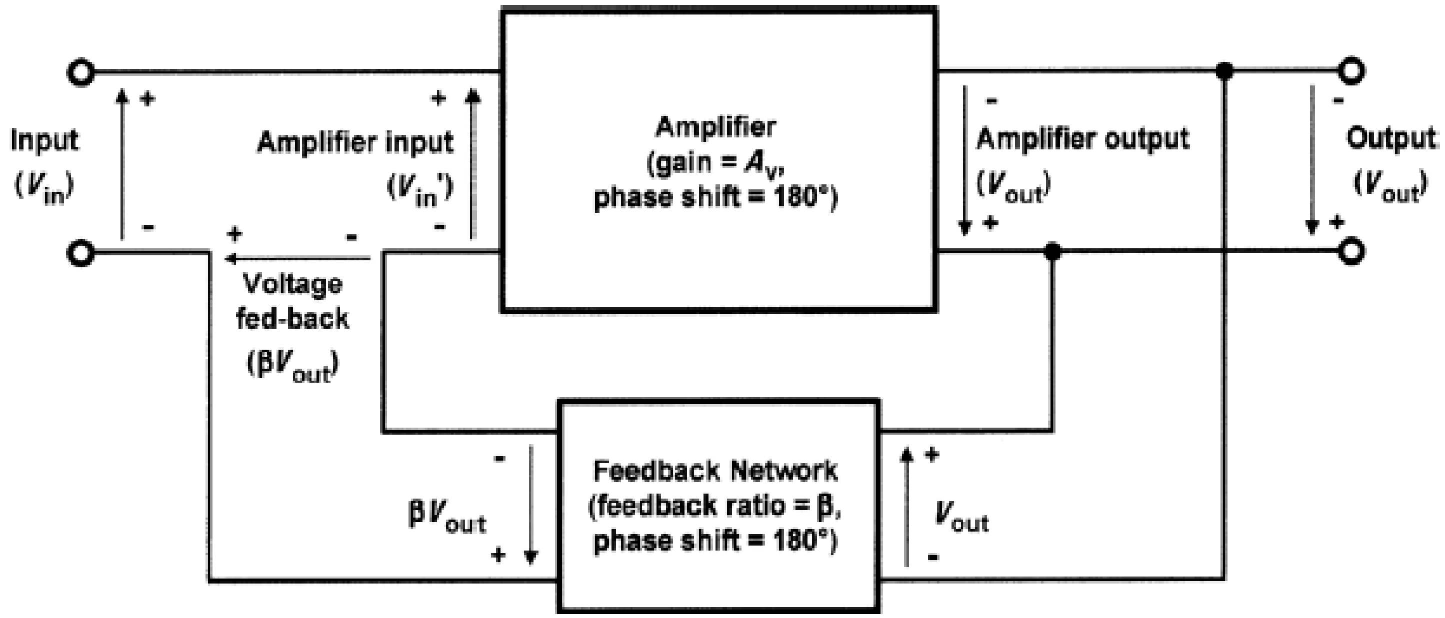
- The bandwidth of an amplifier is usually taken as the difference between the upper and lower cut-off frequencies (i.e. f2 – f1)
- The bandwidth of an amplifier must be sufficient to accommodate the range of frequencies present within the signals that it is to be presented with.
- Many signals contain harmonic components (i.e. signals at 2f, 3f, 4f, etc. where f is the frequency of the fundamental signal).
- It is desirable for an amplifier's bandwidth to greatly exceed the highest signal frequency that it is required to handle!

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.
- Conventional single-stage transistor amplifiers provide phase shifts of either 180° or 360°.

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



Equations

$$\text{Overall gain, } G = \frac{V_{out}}{V_{in}}$$

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

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

$$\text{Overall gain, } G = \frac{A_v \times V'_{in}}{V'_{in} + \beta V_{out}} = \frac{A_v \times V'_{in}}{V'_{in} + \beta(A_v \times V'_{in})}$$

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

Overall gain with negative feedback applied will be less than the gain without feedback. Loop gain is defined as the product of β and *A*v. If *A*v is very large (as is the case with an operational amplifier) the overall gain with negative feedback applied will be given by:

$G = 1/\beta$ (when A_v is very large)

Problems 7 and 8

7. 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. $\beta = 0.1$). Determine the overall voltage gain with negative feedback applied.

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

8. If in problem 7, the amplifier's open-loop voltage gain increases by 20%, determine the percentage increase in overall voltage gain.

$$A_v = A_v + 0.2A_v = 1.2 \times 50 = 60$$

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

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: One of the important benefits of negative feedback in stabilizing the overall gain of an amplifier stage.

Problem 9

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.

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

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

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

Multi-stage amplifiers

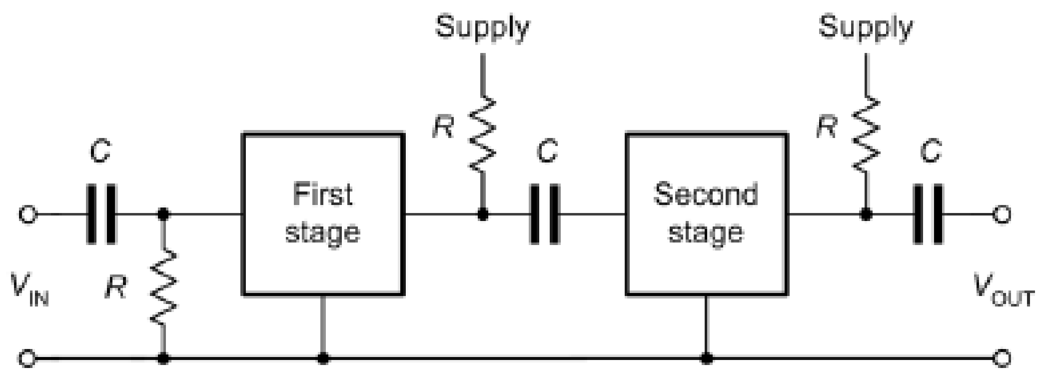
- In order to provide sufficiently large values of gain, it is frequently necessary to use a number of interconnected stages within an amplifier.
- The overall gain of an amplifier with several stages (i.e. a multi-stage amplifier) is simply the product of the individual voltage gains.

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

- 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.

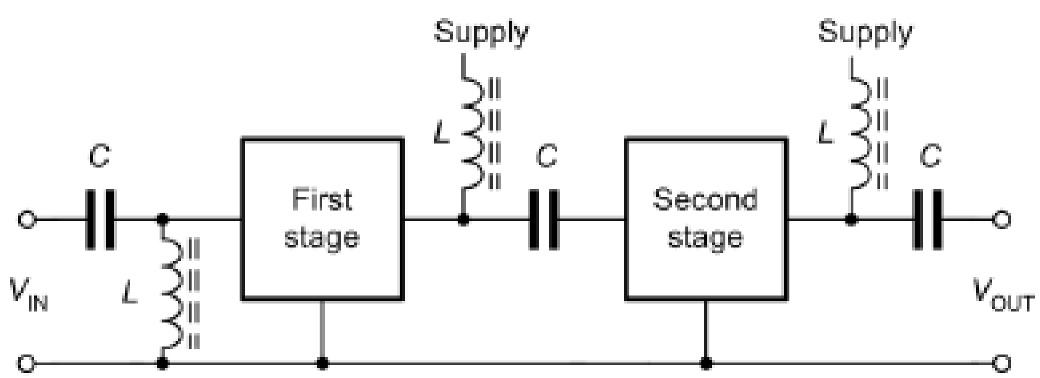
Different types of coupling used in multi-stage amplifiers

- R – C coupling: The stages are coupled together using capacitors having a low reactance at the signal frequency and resistors.



(a) Typical R–C coupling between stages

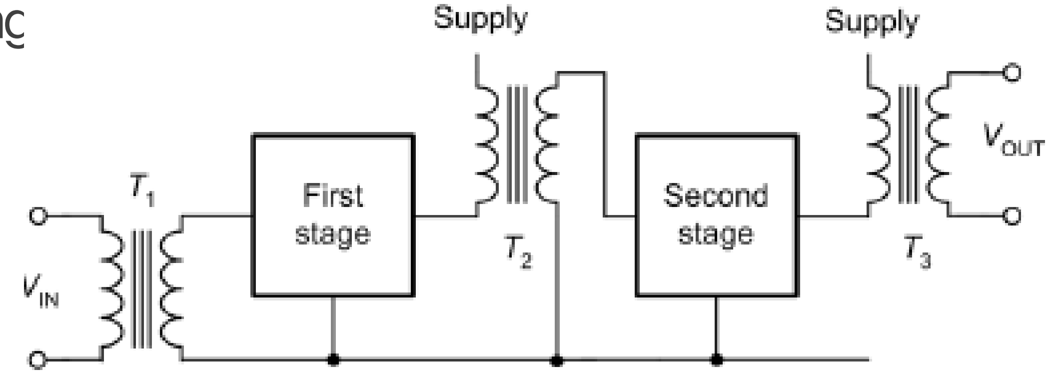
- L – C coupling: inductors have a high reactance at the signal frequency. This type of coupling is generally only used in RF and high-frequency amplifiers.



(b) Typical L–C coupling between stages

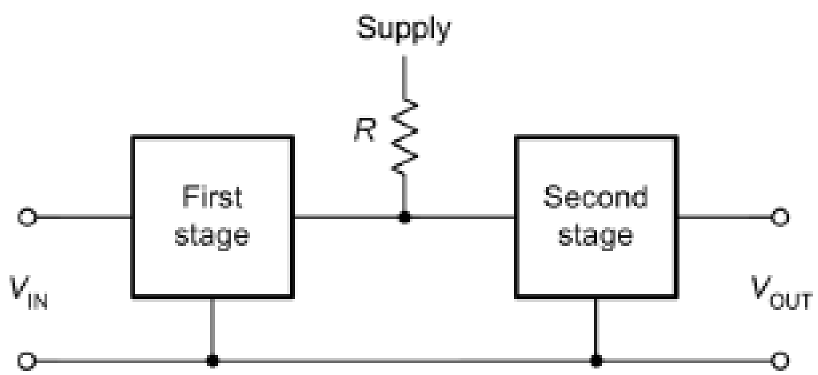
Different types of coupling used in multi-stage amplifiers

- Transformer coupling



(c) Typical transformer coupling between stages

- Direct coupling: DC levels are preserved



(d) Typical direct coupling between stages

operational amplifier:Introduction

An operational amplifier (or OP AMP) is a very high gain differential amplifier with high input impedance and low output impedance.

Op amp offer all the advantages of monolithic integrated circuit such as small size, high reliability, reduced cost and less power consumption.

Op amps are used in used in applications such as adder, subtractor, multiplier, integrator, differentiator, rectifier, comparator, instrumentation amplifiers etc.

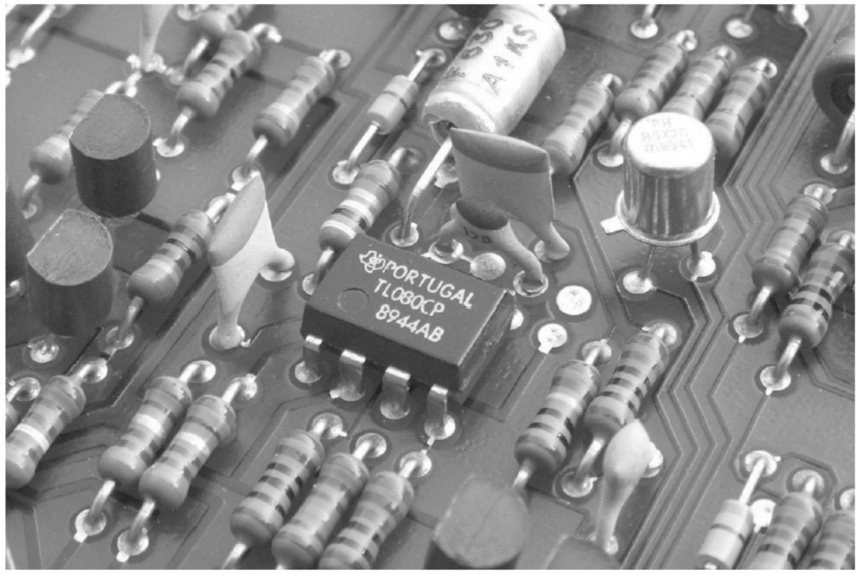


Figure 8.1 A typical operational amplifier.

Symbols and Connections

The device has two inputs i.e. inverting input & non-inverting input and one output and no common connection.

Inverting input is marked by "–" sign & Non-inverting input is marked by "+" sign.

The '+' sign indicates zero phase shift while the '–' sign indicates 180° phase shift.

Opamp requires symmetrical supplies i.e. positive and negative rail supply (±6 V to ±15 V) to allow the output voltage to swing both positive (above 0 V) and negative (below 0 V).

The common connection to these two supplies (0 V supply) acts as the common rail.

All the input and output voltages are usually measured relative to common rail.

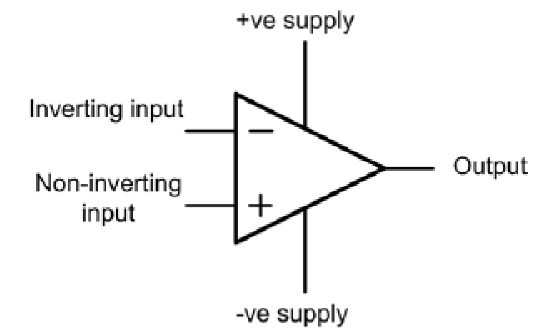


Figure 8.2 Symbol for an operational amplifier

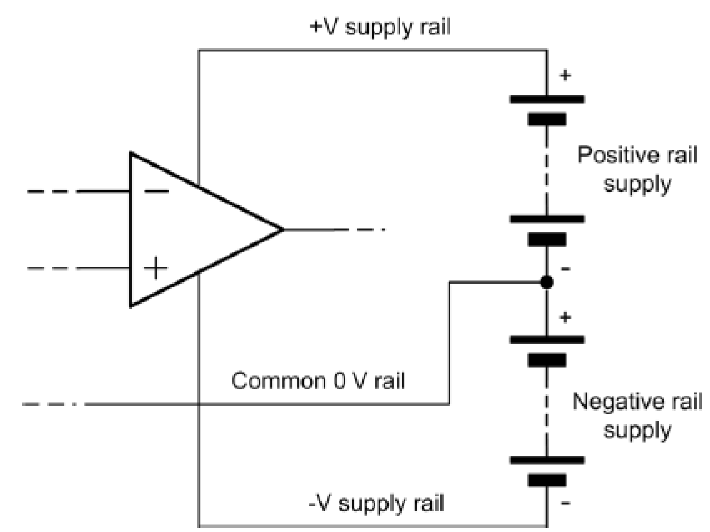


Figure 8.3 Supply connections for an operational amplifier

Operational Amplifier Parameters

The various operational amplifier parameters are as follows:

a) Open loop gain

b) Closed loop gain

c) Input Resistance

d) Output Resistance

e) Input offset voltage

f) Full Power Bandwidth

g) Slew Rate

Operational Amplifier Parameters

a) Open-loop voltage gain

- It is ratio of output voltage to input voltage measured with no feedback applied.
- Open loop gain ($A_{V(OL)}$) is the internal voltage gain of opamp and is given by expression

$$A_{V(OL)} = \frac{V_{out}}{V_{in}}$$

- In decibels,

$$A_{V(OL)} = 20\log\frac{V_{out}}{V_{in}}$$

where V_{in} & V_{out} is the input & output voltage respectively under open loop conditions.

- Most operational amplifiers have very high open-loop voltage gains values (Typically $A_{V(OL)} > 100000$ or $A_{V(OL)} > 90$ dB).

Operational Amplifier Parameters

b) Closed-loop voltage gain

- It is ratio of output voltage to input voltage measured with negative feedback applied.
- Open loop gain ($A_{V(CL)}$) is the internal voltage gain of opamp and is given by expression

$$A_{V(CL)} = \frac{V_{out}}{V_{in}}$$

- In decibels,

$$A_{V(CL)} = 20\log\frac{V_{out}}{V_{in}}$$

where V_{in} & V_{out} is the input & output voltage respectively under closed loop conditions.

- Closed-loop voltage gain is normally very much less than the open-loop voltage gain.

Operational Amplifier Parameters

c) Input Resistance

- It is defined as ratio of input voltage to input current and is given by expression:

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

where 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).

- The input of an operational amplifier is purely resistive at lower frequencies.
- However, at high frequencies the shunt capacitive reactance become more significant.
- 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 10^{12} Ω for FET and CMOS devices.

Operational Amplifier Parameters

d) Output Resistance

- It is defined as ratio of open-circuit output voltage to short-circuit output current and is given by expression:

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

where where R_{out} is the output resistance (in ohms), $V_{out(OC)}$ is the open-circuit output voltage (in volts) and I_{out} is the short-circuit output current (in amps).

- Typical values of output resistance range from less than 10 Ω to around 100 Ω, depending upon the configuration and amount of feedback employed.

Operational Amplifier Parameters

e) Input offset voltage

- An ideal operational amplifier would provide zero output voltage when 0 V 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.
- If AC rather than DC coupling is employed, offset voltage is not normally a problem and can be happily ignored.

Operational Amplifier Parameters

f) Full Power Bandwidth

- It is equivalent to the frequency at which the maximum undistorted peak output voltage swing falls to 0.707 of its low-frequency (DC) value.

- Typical full-power bandwidths range from 10 kHz to over 1 MHz for some high-speed devices.

Operational Amplifier Parameters

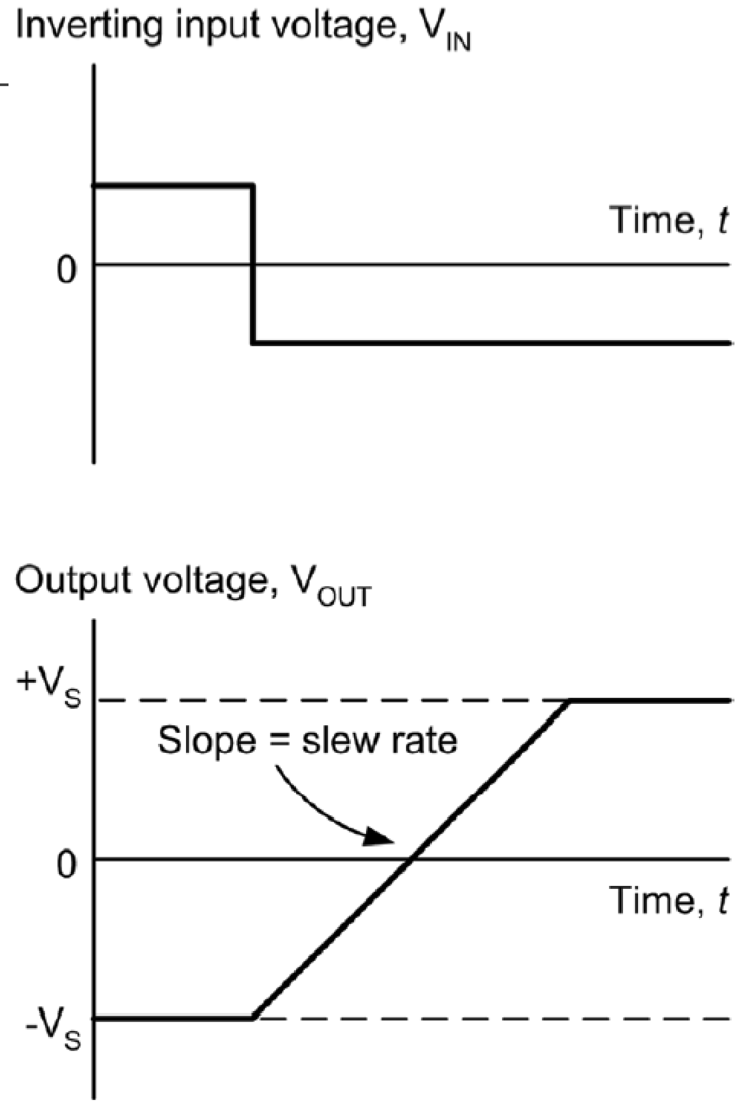
g) Slew Rate

- It is is the rate of change of output voltage with time in response to a perfect step-function input and is given by expression:

$$SR = \frac{\Delta V_{out}}{\Delta t}$$

where ΔV_{OUT} is the change in output voltage (in volts) and Δt 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.



Slew rate for an operational amplifier

Example 8.1

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.

$$(A_v)_{CL} = \frac{V_{out}}{V_{in}} = \frac{2}{400\cdot 10^{-6}} = 5000$$

$$\left[(A_v)_{CL}\right]_{dB} = 20\log 5000 = 74dB$$

Example 8.2

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

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

$$\Rightarrow I_{in} = \frac{V_{in}}{R_{in}} = \frac{5\cdot 10^{-3}}{2\cdot 10^{6}} = 2.5nA$$

Example 8.3

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.

$$Slew\,Rate = \frac{\Delta V_{out}}{\Delta t} = \frac{10}{4 \cdot 10^{-6}} = 2.5V/\mu s$$

Example 8.4

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.

$$Slew\,Rate = \frac{\Delta V_{out}}{\Delta t}$$

$$\Rightarrow \Delta t = \frac{\Delta V_{out}}{Slew\,Rate}$$

The output voltage change will be 20 · 100 = 2,000 mV (or 2 V).

$$t = \frac{2V}{15V/\mu s} = 0.133\mu s$$

Operational Amplifier Characteristics

The desirable characteristics for an 'ideal' operational amplifier are:

a) Open-loop voltage gain should be very high (ideally infinite).
b) Input resistance should be very high (ideally infinite).
c) 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.

Table 8.1 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

- 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 8.1.

Operational Amplifier Configurations

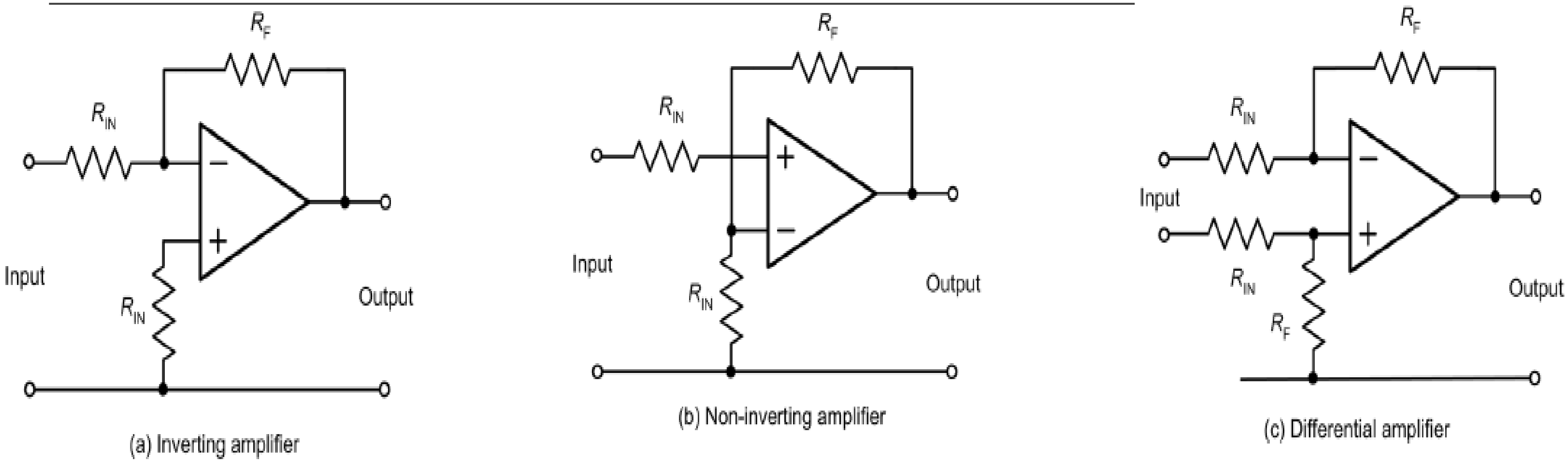


Figure 8.7 The three basic configurations for operational voltage amplifiers

Effect of Adding Capacitors

- Input capacitor (C_{IN}) and feedback capacitors (C_F) of appropriate value may be inserted in series with the input resistor, R_{IN}, and in parallel with the feedback resistor, R_F.
- The value of capacitors are chosen so as to roll-off the frequency response of the amplifier at the desired lower and upper cut-off frequencies, respectively.
- The lower cut-off frequency (f_1) is determined by the value of the input capacitance, C_{IN}, and input resistance, R_{IN}.
- The upper cut-off frequency (f_2) is determined by the feedback capacitance, C_F, and feedback resistance, R_F.
- The lower & upper cut-off frequency is given by:

$$f_1 = \frac{1}{2\pi R_{IN} C_{IN}} = \frac{0.159}{R_{IN} C_{IN}} \qquad f_2 = \frac{1}{2\pi R_F C_F} = \frac{0.159}{R_F C_F}$$

- where f_1 is the lower cut-off frequency in hertz, C_{IN} is in farads and R_{IN} is in ohms & f_2 is the upper cut-off frequency in hertz, C_F is in farads and R_2 is in ohms.

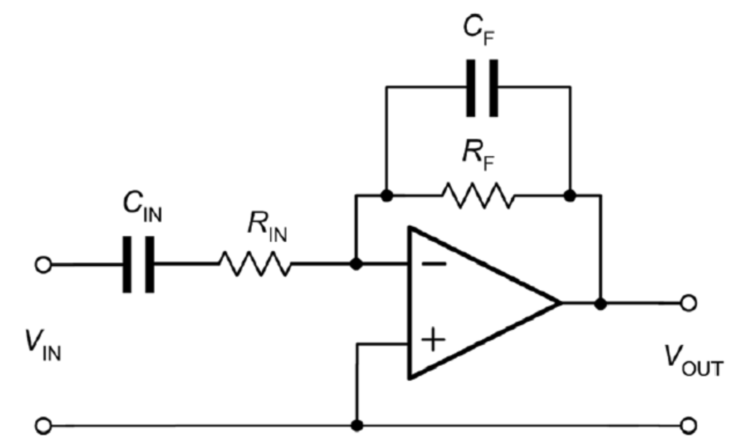


Figure 8.8 Adding capacitors to modify the frequency response of an inverting operational amplifier

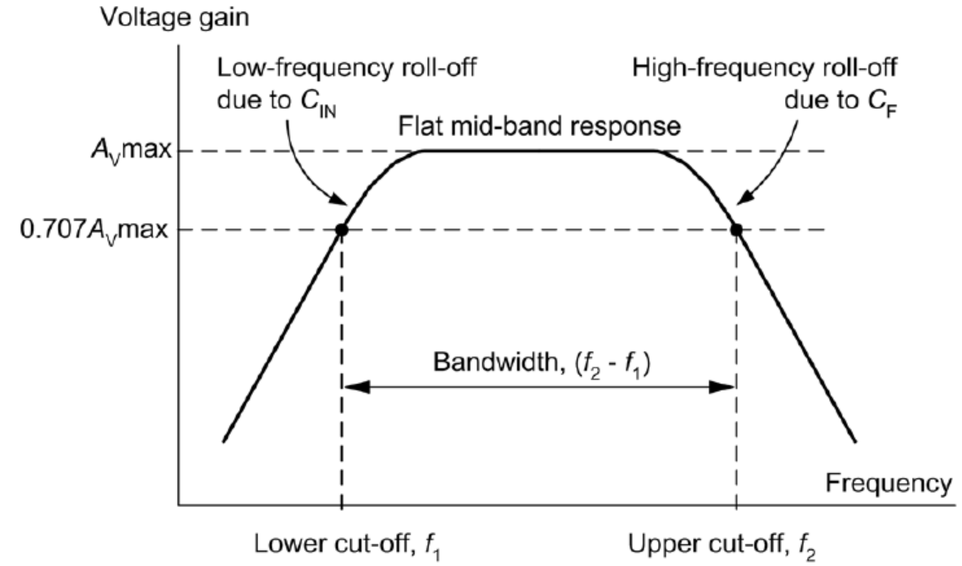


Figure 8.9 Effect of adding capacitors, C_{IN} and C_F, to modify the frequency response of an operational amplifier

Example 8.6

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.

The nominal input resistance is the same as the value for R_{IN}.

$$R_{in} = 10K\Omega$$

Mid-band voltage gain $A_V = \frac{R_F}{R_{in}} \Rightarrow R_F = A_V \cdot R_{in} = 100 \cdot 10K\Omega = 1000K\Omega$

Lower cut-off frequency $f_1 = \frac{0.159}{R_{in}C_{IN}} \Rightarrow C_{IN} = \frac{0.159}{R_{in} f_1} = \frac{0.159}{10 \cdot 10^3 \cdot 250} = 63nF$

Higher cut-off frequency $f_2 = \frac{0.159}{R_F C_F} \Rightarrow C_F = \frac{0.159}{R_F f_2} = \frac{0.159}{100 \cdot 10^3 \cdot 15 \cdot 10^3} = 106pF$

Operational Amplifier Circuits

As well as their application as a general-purpose amplifying device, operational amplifiers have a number of other applications such as :

a) Voltage Follower

b) Differentiator

c) Integrator

d) Summing Amplifier

Operational Amplifier Circui

a) <u>Voltage follower</u>

- This circuit is essentially an inverting amplifier in which 100% of the output is fed back to the input.
- The expression is given by:

$$V_{OUT} = V_{IN}$$

- 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.

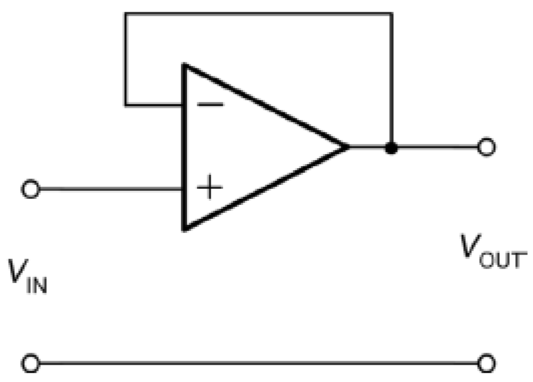


Figure 8.11 A voltage follower

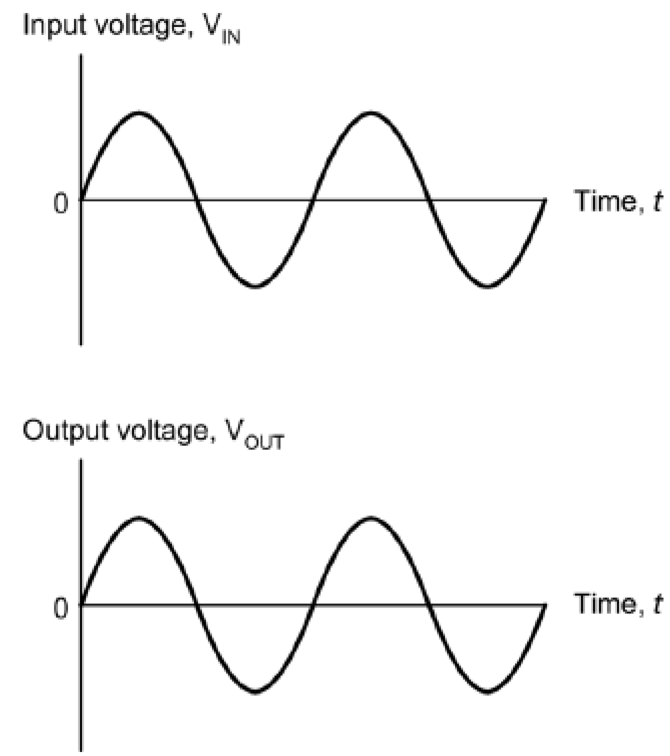


Figure 8.12 Typical input and output waveforms for a voltage follower

Operational Amplifier Circuits

Differentiator

A differentiator produces an output voltage that is equivalent to the rate of change of its input.

- The expression is given by:

$$V_{OUT} = -RC\frac{dV_{IN}}{dt}$$

Integrator

- An integrator produces an output which is equivalent to the area under the graph of the input function.
- The expression is given by:

$$V_{OUT} = -\frac{1}{RC}\int V_{IN}dt$$

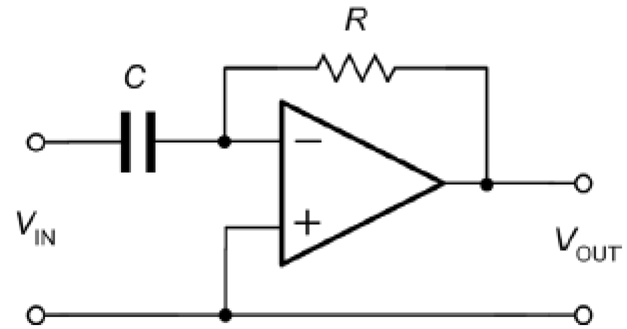


Figure 8.13 A differentiator

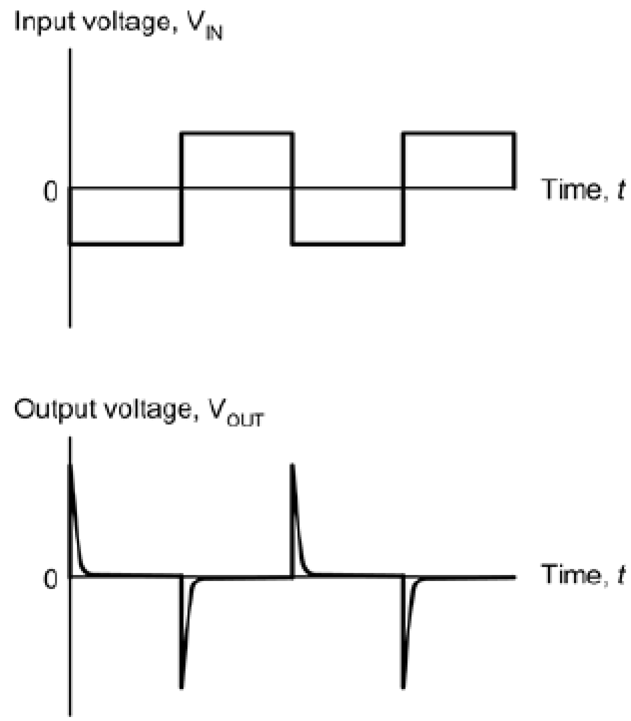


Figure 8.14 Typical input and output waveforms for a differentiator

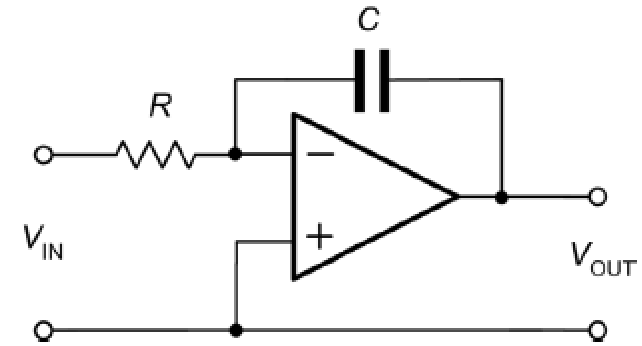


Figure 8.15 An integrator

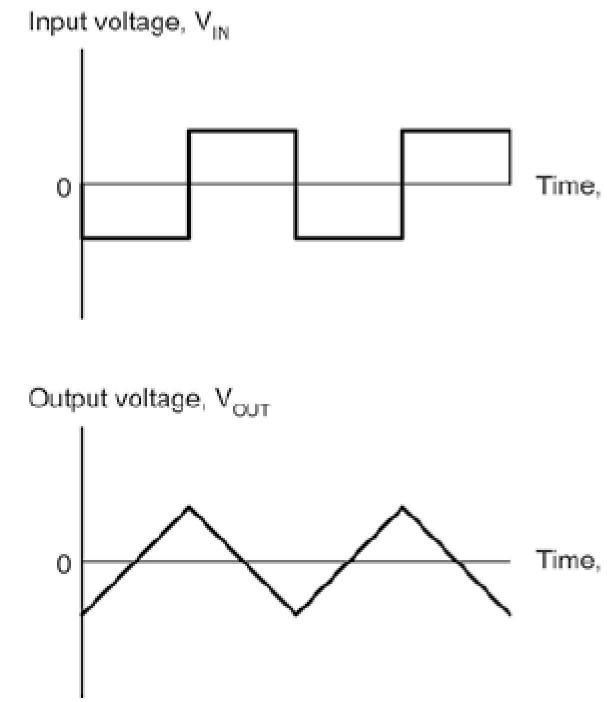


Figure 8.16 Typical input and output waveforms for an integrator

Operational Amplifier Circuits

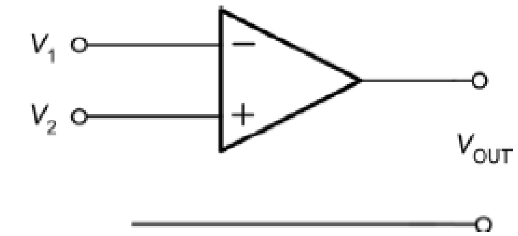


Figure 8.17 A comparator

Comparator

- Comparator is a circuit which compares the voltage at the inverting & non-inverting input terminals.
- When non-inverting input voltage exceeds the inverting input, output voltage will thus rise to the maximum possible value (equal to the positive supply rail voltage).
- Conversely, when inverting input voltage exceeds the non-inverting input, output voltage will thus rise to the minimum possible value (equal to the negative supply rail voltage).
- 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.

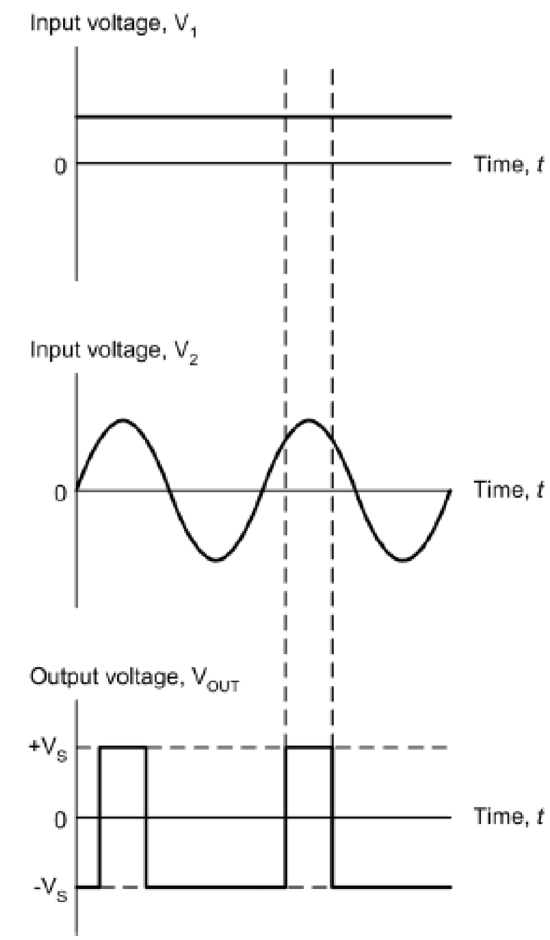


Figure 8.18 Typical input and output waveforms for a comparator

Operational Amplifier Circuits

Summing amplifiers

- A summing amplifier is a circuit that produces an output that is the sum of its two input voltages.
- Since the operational amplifier is connected in inverting mode, the output voltage is given by:

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

where V_1 and V_2 are the input voltages.

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

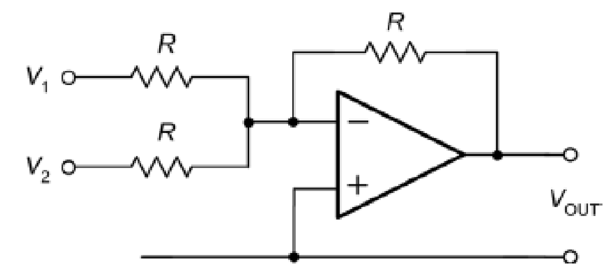


Figure 8.19 A summing amplifier

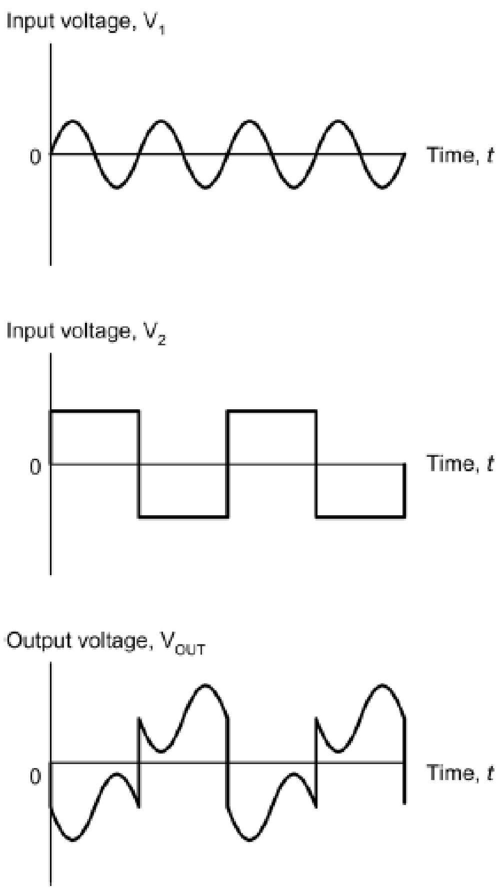


Figure 8.20 Typical input and output waveforms for a summing amplifier

Positive feedback

Positive feedback is 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).

The overall voltage gain (G) of amplifier with positive feedback is given by:

$$G = \frac{V_{OUT}}{V_{IN}} = \frac{A_v}{1 - \beta A_v}$$

where A_V is the internal gain of the amplifier & β is the proportion of the output voltage fed back to the input.

- when the loop gain, βA_V, approaches unity. The denominator (1 − βAv) will become close to zero.
- Therefore, the overall gain with positive feedback applied will be greater than the gain without feedback.
- This form of feedback is used in oscillator circuits.

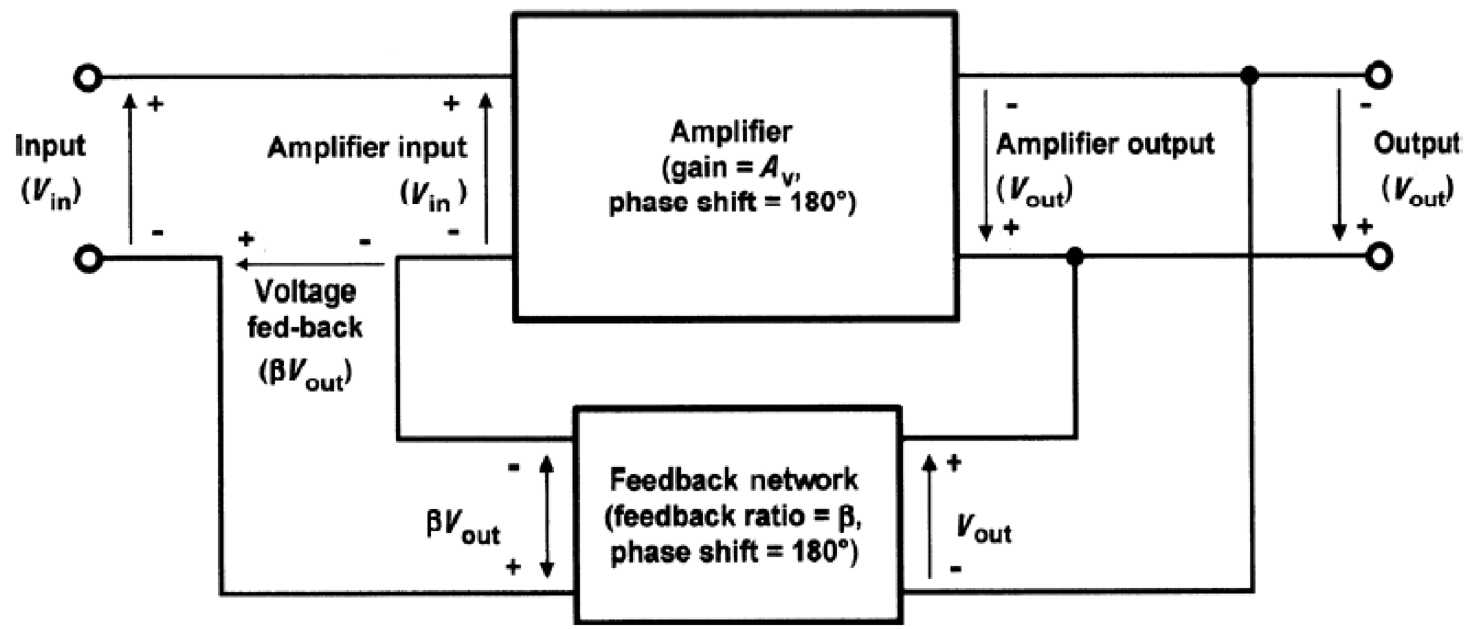


Figure 9.1 Amplifier with positive feedback applied

Oscillators

- Oscillators are the circuits that generate an output signal without the need for an input signal.
- When the loop gain approaches unity (or larger), it results in unstable amplifier with infinite gain.
- In such case, amplifier will oscillate since any disturbance will be amplified and result in an output.
- Therefore, positive feedback have an undesirable effect i.e. instead of reducing the overall gain it reinforces any signal present and the output continuous oscillates if the loop gain is 1 or greater.

Condition for Oscillations

There are two 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).

To create an oscillator, an amplifier with sufficient gain is needed to overcome the losses of the network that provide positive feedback.

If the amplifier provides 180° phase shift, the frequency of oscillation will be that at which there is 180° phase shift in the feedback network.

Alternatively, if the amplifier produces 0° phase shift, the circuit will oscillate at the frequency at which the feedback network produces 0° phase shift.

Positive feedback is needed in both cases so that the output signal arrives back at the input in such a sense as to reinforce the original signal.

Ladder Network Oscillator

A phase shift oscillator based on 3-stage C – R ladder network can be used to provide 180° phase shift.

Here, TR_1 operates as a conventional common-emitter amplifier stage with R_1 and R_2 providing base bias potential and R_3 and C_1 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° (note that these are the same).

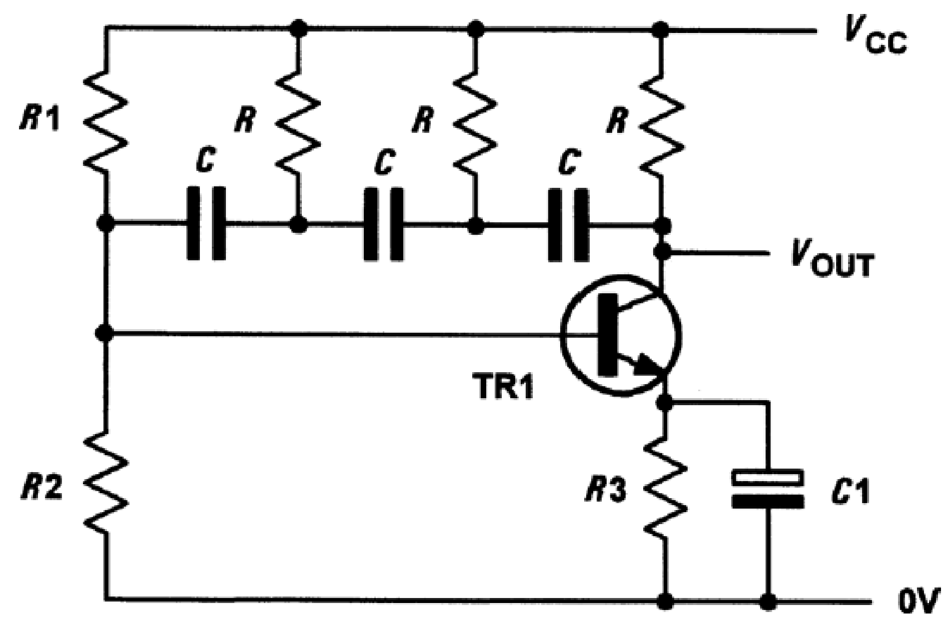


Figure 9.2 Sine wave oscillator based on a three stage *C–R* ladder network

- The frequency of oscillation is $$f_{osc} = \frac{1}{2\pi RC\sqrt{6}}$$

- 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.

Wien Bridge Oscillator

A phase shift oscillator based a Wien bridge network can be used to provide 0° phase shift.

Similar to C − R ladder, this network provides a phase shift which varies with frequency.

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.

If an amplifier producing 0° phase shift is connected which has sufficient gain to overcome the losses of the Wien bridge, oscillations will result.

The frequency at which the phase shift will be zero is:

$$f_{osc} = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

The minimum amplifier gain required to sustain oscillation is:

$$A_v = 1 + \frac{C_1}{C_2} + \frac{R_2}{R_1}$$

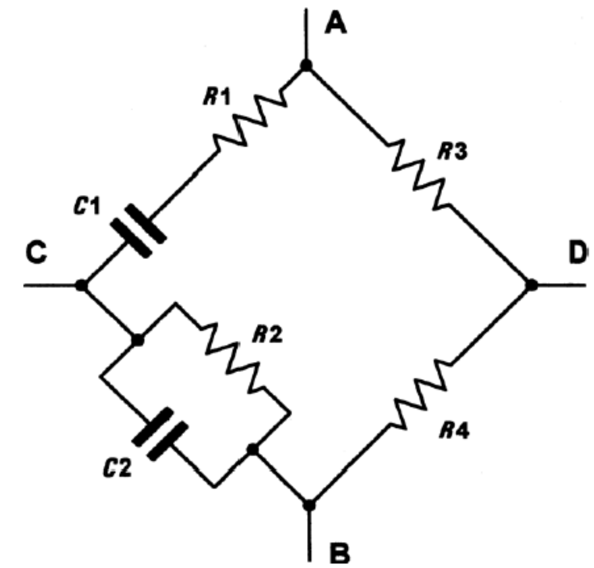


Figure 9.3 A Wien bridge network

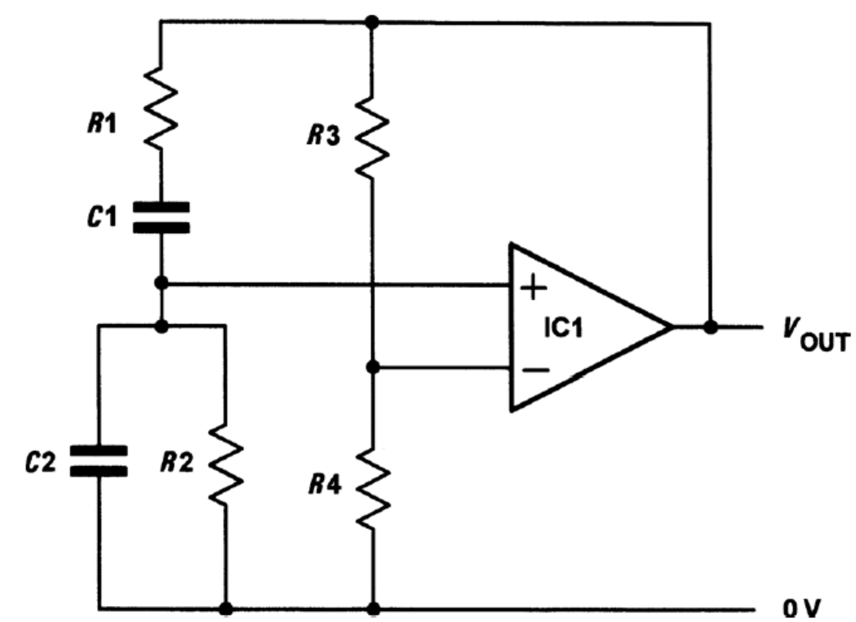


Figure 9.4 Sine wave oscillator based on a Wien bridge network

Example 9.1

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

The frequency of oscillation

$$f_{osc} = \frac{1}{2\pi RC\sqrt{6}} = \frac{1}{2\cdot 3.14\cdot 10\cdot 10^{3}\cdot 10\cdot 10^{-9}\cdot \sqrt{6}} = 647\,Hz$$

Example 9.2

Fig. 9.4 shows the circuit of a Wien bridge oscillator based on an operational amplifier.
If $C_1 = C_2 = 100$ nF, determine the output frequencies produced by this arrangement (a) when $R_1 = R_2 = 1$ kΩ and (b) when $R_1 = R_2 = 6$ kΩ.

(a) When $R_1 = R_2 = 1\ K\Omega$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then

$$f_{osc} = \frac{1}{2\pi RC} = \frac{1}{2\cdot 3.14\cdot 1\cdot 10^{3}\cdot 100\cdot 10^{-9}} = 1.59\,KHz$$

(a) When $R_1 = R_2 = 6\ K\Omega$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then

$$f_{osc} = \frac{1}{2\pi RC} = \frac{1}{2\cdot 3.14\cdot 6\cdot 10^{3}\cdot 100\cdot 10^{-9}} = 265\,Hz$$

Multivibrators

Multivibrators are a family of oscillator circuits that produce output waveforms consisting of one or more rectangular pulses.

They generate square wave output from an oscillator rather than a sine wave output.

Multivibrators use regenerative (i.e. positive) feedback; the active devices present within the oscillator circuit being operated as switches, being alternately cut-off and driven into saturation.

The principal types of multivibrator are:

a) **Astable Multivibrators**

   They provide a continuous train of pulses (Also referred to as free-running multivibrators);

b) **Monostable multivibrators**

   They produce a single output pulse (they have one stable state and are also referred to as 'one-shot' multivibrators);

c) **Bistable multivibrators**

   They have two stable states and require a trigger pulse or control signal to change from one state to another.

Single-Stage Astable Oscillator

A simple form of astable oscillator that produces a square wave output can be built using just one operational amplifier.

The circuit employs positive feedback with the output fed back to the non-inverting input via the potential divider formed by R1 and R2.

This circuit can make a very simple square wave source with a frequency that can be made adjustable by replacing R with a variable or preset resistor.

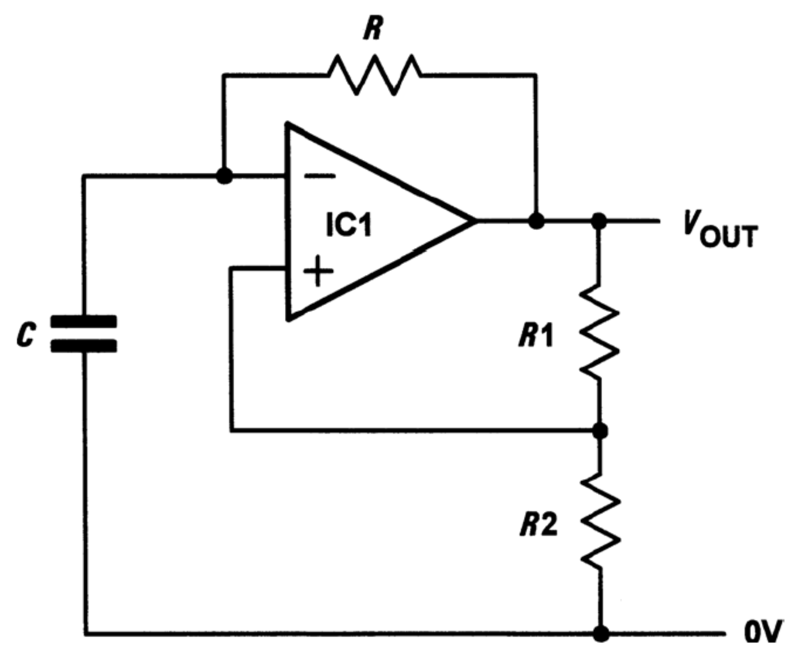


Figure 9.10 Single-stage astable oscillator using an operational amplifier

Single-Stage Astable Oscillator

- Assume that C is initially uncharged and the voltage at the inverting input is slightly less than the voltage at the non-inverting input.
- The output voltage will rise rapidly to $+V_{CC}$ and the voltage at the inverting input will begin to rise exponentially as capacitor C charges through R.
- Eventually the voltage at the inverting input will have reached a value that causes the voltage at the inverting input to exceed that present at the non-inverting input.

At this point, the output voltage will rapidly fall to $-V_{CC}$. Capacitor C will then start to charge in the other direction and the voltage at the inverting input will begin to fall exponentially.

Eventually, the voltage at the inverting input will have reached a value that causes the voltage at the inverting input to be less than that present at the non-inverting input. At this point, the output voltage will rise rapidly to $+V_{CC}$ once again and the cycle will continue indefinitely.

Upper threshold voltage (i.e. maximum positive value for voltage at inverting input) & Lower threshold voltage (i.e. maximum negative value for voltage at inverting input) is given by:

$$V_{UT} = V_{CC}\left(\frac{R_2}{R_1 + R_2}\right) \qquad V_{LT} = -V_{CC}\left(\frac{R_2}{R_1 + R_2}\right)$$

Finally, time for one complete cycle of the output waveform produced by the astable oscillator is:

$$T = 2RC\ln\left(1 + \frac{2R_2}{R_1}\right)$$

Crystal Controlled Oscillators

Crystal controlled oscillators are used when an exact frequency of oscillation need to be accurately maintained.

Crystal oscillator used quartz crystal as the frequency determining element and operates on the principle of piezoelectric effect.

During piezoelectric effect, whenever a potential difference is applied across its faces of quartz crystal, the crystal oscillates.

The frequency of oscillation is determined by the crystal's 'cut' and physical size.

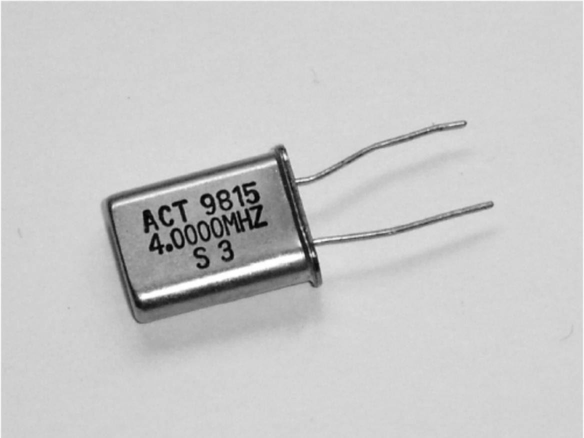


Figure 9.11 A quartz crystal (this crystal is cut to be resonant at 4 MHz and is supplied in an HC18 wire-ended package)