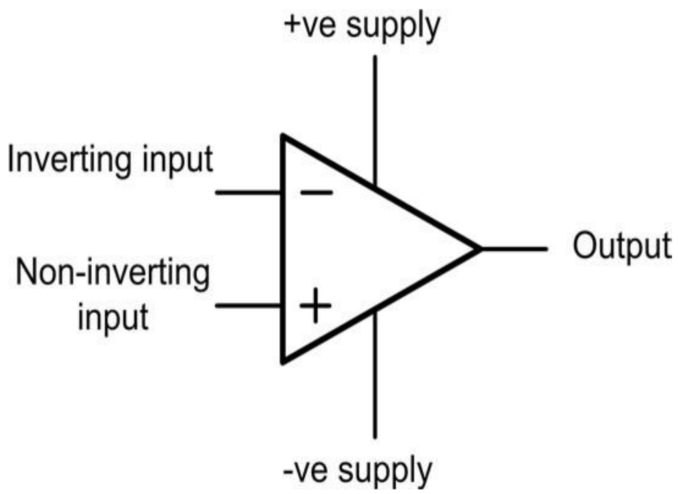
Module-2

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.

Operational amplifier:

- The symbol for an operational amplifier is shown in Fig.
- The device has two inputs and one output and no common connection.
- In Fig., one of the inputs is marked '−' and the other is marked '+'.
- 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.



Operational amplifier parameters:

1. Open-loop voltage gain
2. Closed-loop voltage gain
3. Input resistance
4. Output resistance
5. Input offset voltage
6. Full-power bandwidth
7. Slew rate

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.

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

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. Typically greater than 100,000.

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

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

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).

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

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.

Input resistance:

The input resistance of an operational amplifier is defined as the ratio of input voltage to input current expressed in ohms.

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

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). In practice values range from about 2MΩ for common bipolar types to over 10^{12} Ω for FET and CMOS devices.

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.

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

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

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.
Typical values of input offset voltage range from 1 Mv to 15 mV.

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 (the sinusoidal input voltage remaining constant).
Typical full-power bandwidths range from 10 kHz to over 1 MHz for some high-speed devices.

Slew rate:
Slew rate is the rate of change of output voltage with time, when a rectangular step input voltage is applied.

$$SLEW\ RATE = \frac{\Delta V_{OUT}}{\Delta t}$$

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.

Operational amplifier characteristics:

Characteristics for an 'ideal' operational amplifier are:

(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.

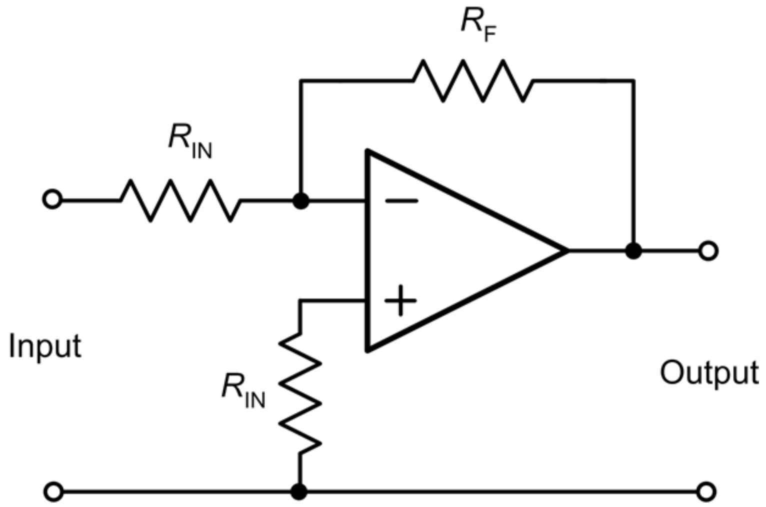
(e) Slew rate should be as large as possible.

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

Operational amplifier configurations:
The three basic configurations for operational voltage amplifiers are

1. Inverting Amplifier
2. Non-Inverting Amplifier
3. Differential Amplifier

1. Inverting Amplifier:
An Inverting Amplifier configuration using an operational amplifier is as shown in Fig.



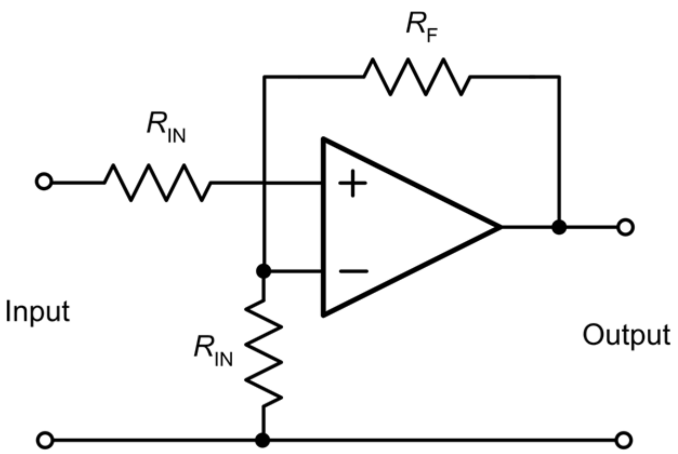
Output voltage

$$V_{OUT} = -\frac{R_F}{R_{IN}} V_{IN}$$

Closed-loop gain for inverting amplifier is given by:

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

2. Non-Inverting Amplifier:
An non-Inverting Amplifier configuration using an operational amplifier is as shown in Fig.



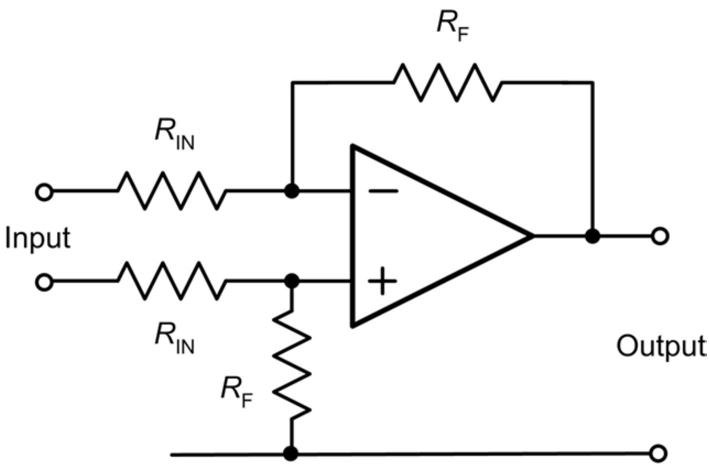
Output voltage

$$V_{OUT} = (1 + \frac{R_F}{R_{IN}})\, V_{IN}$$

Closed-loop gain for inverting amplifier is given by:

$$A_{V(CL)} = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_F}{R_{IN}}$$

3. Differential Amplifier:
A differential Amplifier configuration using an operational amplifier is as shown in Fig.



Output voltage

$$V_{OUT} = \frac{R_F}{R_{IN}}(V_2 - V_1)$$

Closed-loop gain for inverting amplifier is given by:

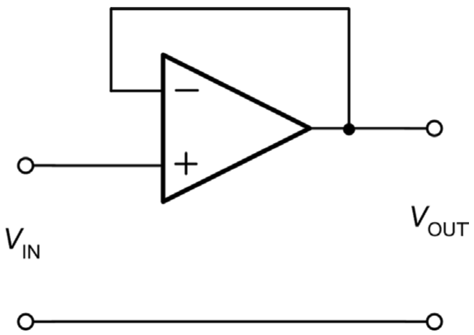
$$A_{V(CL)} = \frac{V_{OUT}}{V_{IN}} = \frac{R_F}{R_{IN}}$$

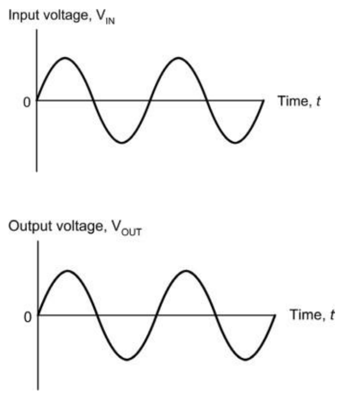
Operational amplifier circuits:
Operational amplifiers have a number of other uses, including voltage followers, differentiators, integrators, comparators, and summing amplifiers.

Voltage followers:

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

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

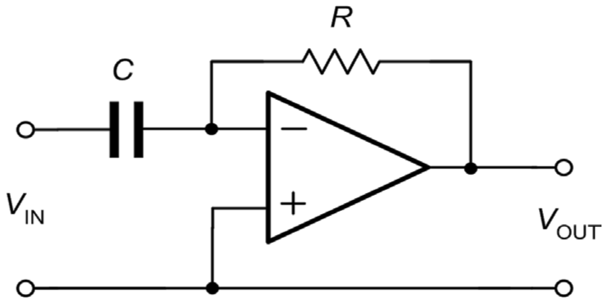


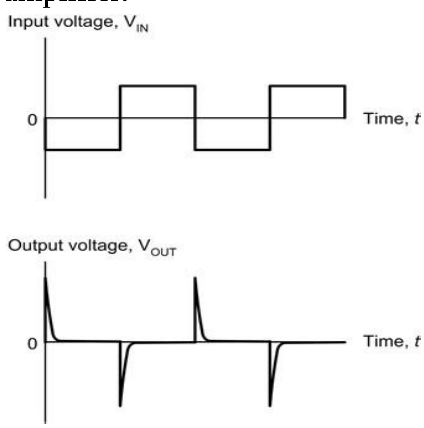


Output voltage: $V_{OUT} = V_{IN}$

Differentiators:

- A differentiator using an operational amplifier is as shown in Fig.
- A differentiator produces an output voltage that is equivalent to the rate of change of its input.
- Typical input and output waveforms for a differentiator are shown in Fig.
- Notice how the square wave input is converted to a train of short duration pulses at the output. Note also that the output waveform is inverted because the signal has been applied to the inverting input of the operational amplifier.

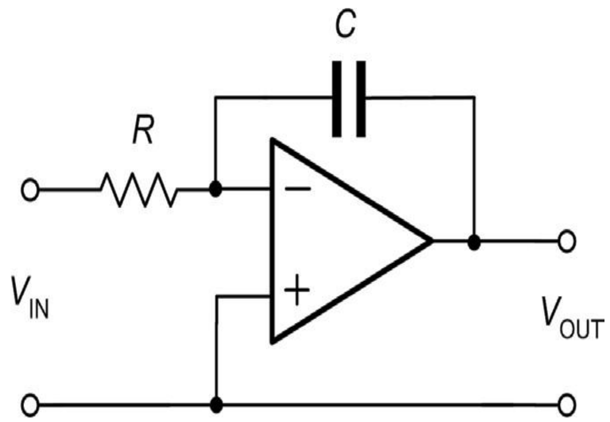


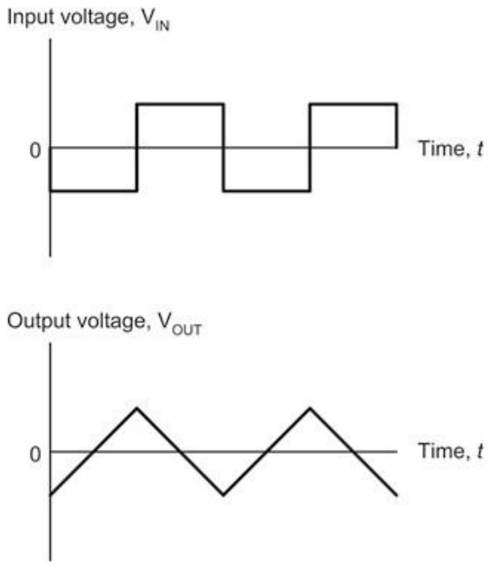


Output voltage $V_{OUT} = -R_F \times C \left(\frac{dV_{IN}}{dx}\right)$

Integrators:

- An integrator using an operational amplifier is shown in Fig.
- 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.
- The longer the input voltage remains at a particular value the larger the value of output voltage (of either polarity) will be produced.
- Typical input and output waveforms for an integrator are shown in Fig. Notice how the square wave input is converted to a wave that has a triangular shape. Once again, note that the output waveform is inverted.

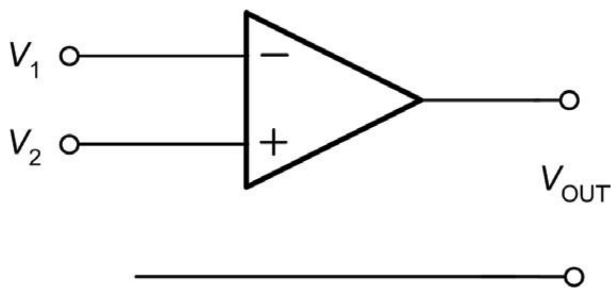


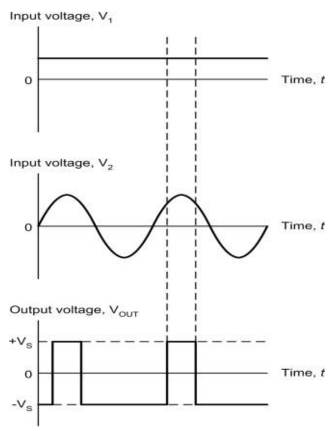


Output voltage $V_{OUT} = -\frac{1}{R_F \times C} \int V_{IN}\, dt$

Comparators:

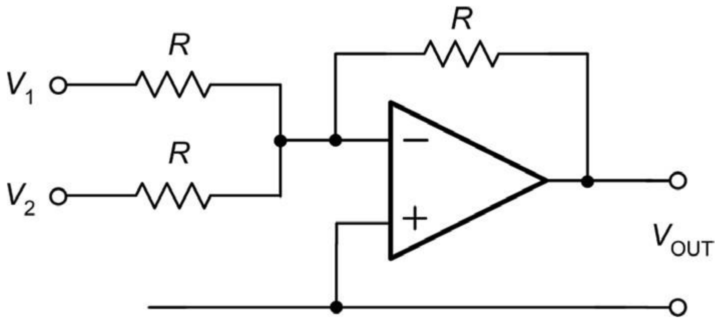
- A comparator using an operational amplifier is shown in Fig.
- Since no negative feedback has been applied, this circuit uses the maximum gain of the operational amplifier.
- The output voltage produced by the operational amplifier will thus rise to the maximum possible value whenever the voltage present 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 whenever the voltage present at the inverting input exceeds that present at the non-inverting input.



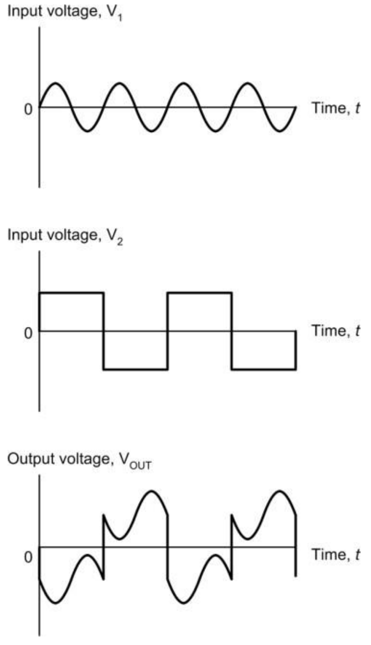


Summing amplifiers:

- A summing amplifier using an operational amplifier is shown in Fig.
- This circuit produces an output that is the sum of its two input voltages.
- However, since the operational amplifier is connected in inverting mode, the output voltage is given by:
- $V_{OUT} = -(V1 + V2)$
- where $V1$ and $V2$ 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.

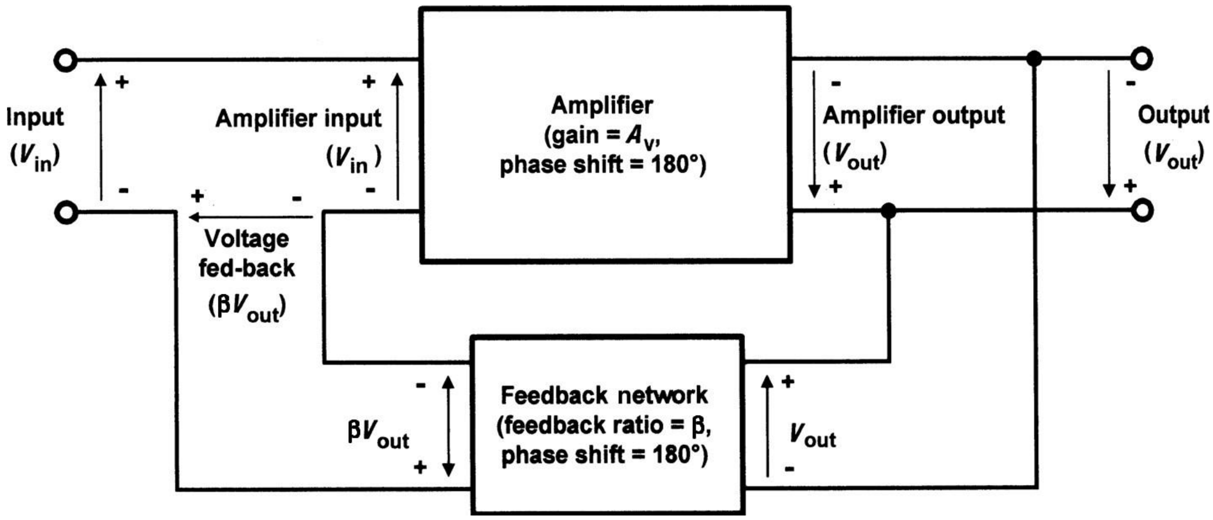


Output voltage $V_{OUT} = -(V_1 + V_2)$



Oscillators

Positive feedback:
Fig. shows the block diagram of an amplifier stage with positive feedback applied.



Note that 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 voltage gain, G, is given by:

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

By applying Kirchhoff's Voltage Law

$$V^{`}_{in} = V_{in} + \beta V_{out}$$

Thus:

$$V_{in} = V^{`}_{in} - \beta V_{out}$$

And

$V_{out} = A_V \times V^{`}_{in}$

Where Av is the internal gain of the amplifier

Hence:

Overall gain, $G = \frac{V_{out}}{V_{in}} = \frac{A_V \times V_{in}}{V^{`}_{in} - \beta V_{out}} = \frac{A_V \times V^{`}_{in}}{V^{`}_{in} - \beta(A_V \times V^{`}_{in})} = \frac{A_V \times V^{`}_{in}}{V^{`}_{in}(1-\beta A_V)} = \frac{A_V}{(1-\beta A_V)}$

$$\therefore \text{Overall gain, } G = \frac{A_V}{(1 - \beta A_V)}$$

Conditions for oscillation

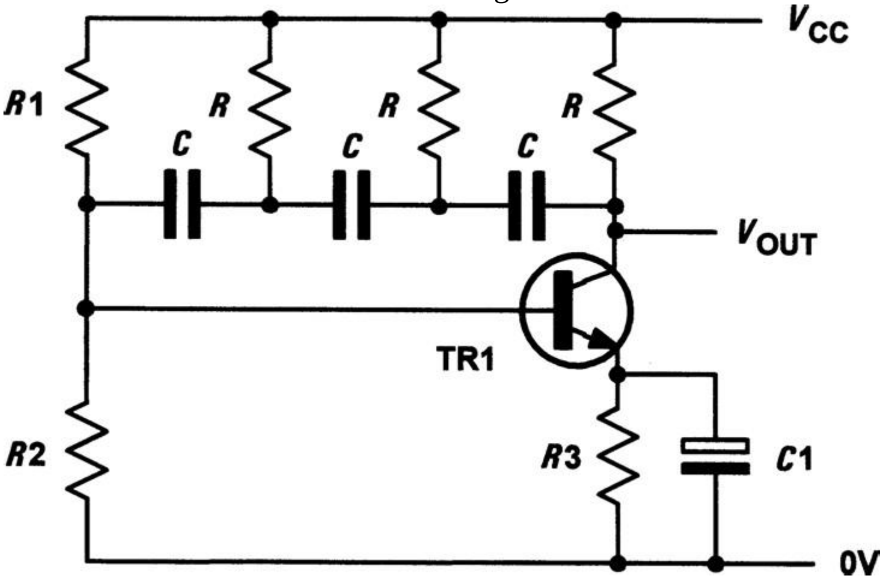
From the foregoing we can deduce that the conditions for oscillation are:

(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).

Ladder network oscillator:

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



TR1 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°.

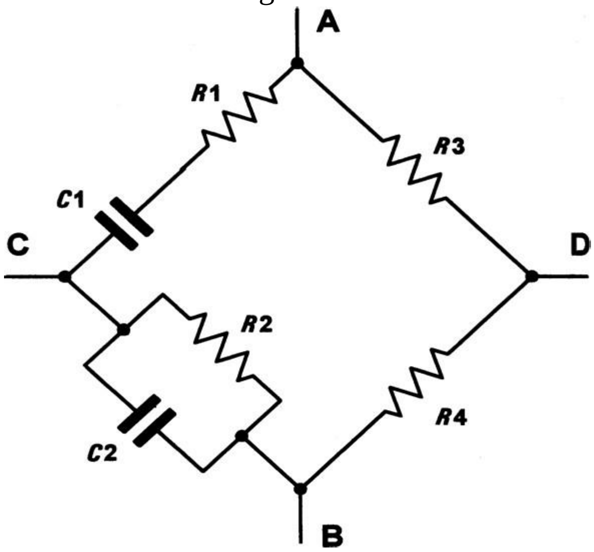
The frequency of oscillation of the circuit shown in Fig. is given by:

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

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. In practice this is easily achieved with a single transistor.

Wien bridge oscillator:

A Wien bridge network is as shown in the figure



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 (i.e. the input and output signals will be in-phase).
If we connect the network to an amplifier producing 0° phase shift which has sufficient gain to overcome the losses of the Wien bridge, oscillation will result.
The minimum amplifier gain required to sustain oscillation is given by:

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

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:

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

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

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

where $R = R1 = R2$ and $C = C1 = C\,2$.

Multivibrators:

- Multivibrators are a family of oscillator circuits that produce output waveforms consisting of one or more rectangular pulses.
- The term ‘multivibrator’ simply originates from the fact that this type of waveform is rich in harmonics (i.e. ‘multiple vibrations’).
- 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:

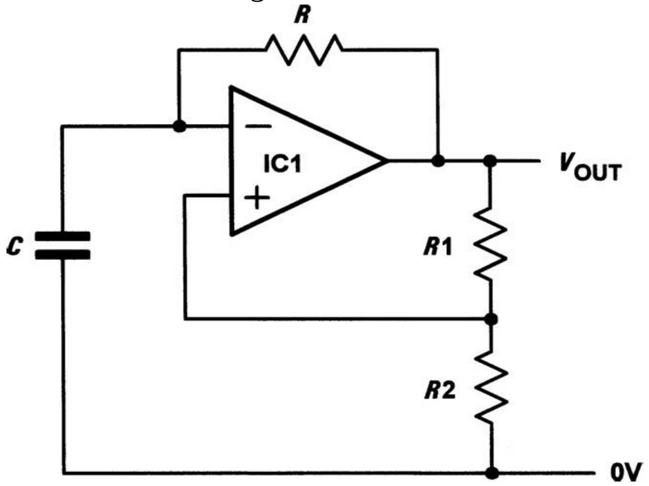
(a) astable multivibrators that provide a continuous train of pulses (these are sometimes also referred to as free-running multivibrators);

(b) monostable multivibrators that produce a single output pulse (they have one stable state and are thus sometimes also referred to as ‘one-shot’);

(c) bistable multivibrators that 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, as shown in Fig



- The circuit employs positive feedback with the output fed back to the non-inverting input via the potential divider formed by *R*1 and *R*2.
- 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.
- 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 +VCC once again and the cycle will continue indefinitely.

- The upper threshold voltage (i.e. the maximum positive value for the voltage at the inverting input) will be given by:

$$V_{UT} = V_{CC} \times (\frac{R_2}{R_1 + R_2})$$

- The lower threshold voltage (i.e. the maximum negative value for the voltage at the inverting input) will be given by:

$$V_{LT} = -V_{CC} \times (\frac{R_2}{R_1 + R_2})$$

Crystal controlled oscillators:

- A requirement of some oscillators is that they accurately maintain an exact frequency of oscillation. In such cases, a quartz crystal can be used as the frequency-determining element.
- The quartz crystal vibrates whenever a potential difference is applied across its faces (this phenomenon is known as the piezoelectric effect).
- The frequency ofoscillation is determined by the crystal's 'cut' and physical size.
- Most quartz crystals can be expected to stabilize the frequency of oscillation of a circuit to within a few parts in a million.
- Crystals can be manufactured for operation in **fundamental mode** over a frequency range extending from 100 kHz to around 20 MHz and for **overtone** operation from 20 MHz to well over 100 MHz.
- Fig. 9.12 shows a simple crystal oscillator circuit in which the crystal provides feedback from the drain to the source of a junction gate FET.