Electronics for 4th semester BSc Physics, Pondicherry University

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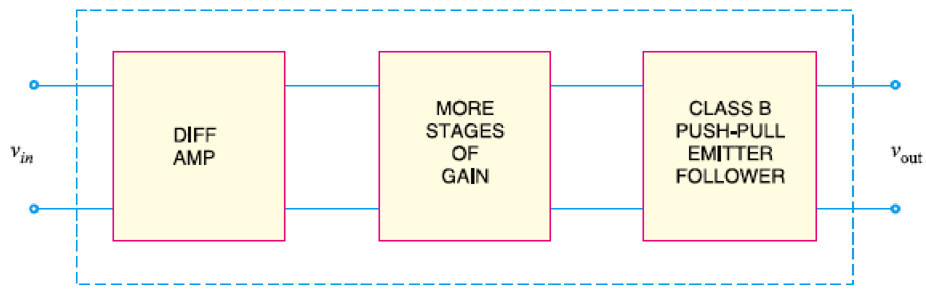
Contents

1 Introduction

An operational amplifier is a multistage amplifier and consists of a differential amplifier stage, a high-gain CE amplifier stage and class B push-pull emitter follower. An operational amplifier (OP-Amp) is an integrated circuit and is widely used in computers, as video and audio amplifiers in communication electronics. Because of their multi-purpose use, OP-Amps are used in all branches of electronics, both digital and linear circuits.

An operational amplifier (OP-Amp) is a circuit that can perform such mathematical operations as addition, subtraction, integration and differentiation

Fig. shows the block diagram of an operational amplifier. Note that OP-Amp is a multistage amplifier. The three stages are : differential amplifier input stage followed by a high-gain CE amplifier and finally the output stage. The key electronic circuit in an OP-Amp is the differential amplifier. A **differential amplifier (DA)** can accept two input signals and amplifies the difference between these two input signals

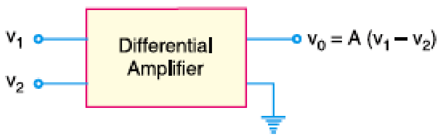


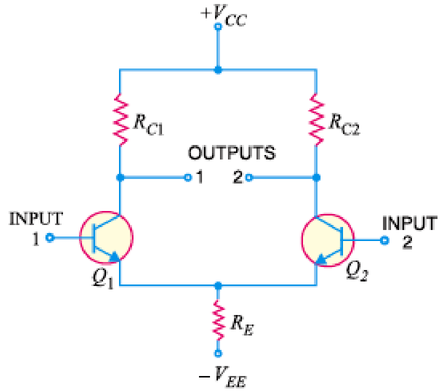
Block diagram of OP-Amp

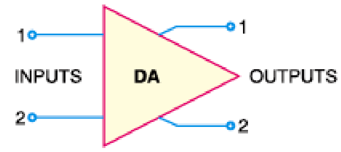
The input stage of an OP-Amp is a differential amplifier (DA) and the output stage is typically a class B push-pull emitter follower. The internal stages of an OP-Amp are direct-coupled i.e., no coupling capacitors are used. The direct coupling allows the OP-Amp to amplify d.c. as well as a.c. signals. An OP-Amp has very high input impedance (ideally infinite) and very low output impedance (ideally zero). The effect of high input impedance is that the amplifier will draw a very small current (ideally zero) from the signal source. The effect of very low output impedance is that the amplifier will provide a constant output voltage independent of current drawn from the source. An OP-Amp has very high *open-loop voltage gain (ideally infinite); typically more than 200,000. The OP-Amps are almost always operated with negative feedback.

1.1 Differential Amplifier

We can design an amplifier circuit that accepts two input signals and amplifies the difference between these two signals. Such an amplifier is called a differential amplifier (DA). A differential amplifier is a circuit that can accept two input signals and amplify the difference between these two input signals. Fig shows the block diagram of a differential amplifier. There are two input voltages v_1 and v. This amplifier amplifies the difference between the two input voltages. Therefore, the output voltage is $V_o = A(v_1 – v_2)$ where A is the voltage gain of the amplifier







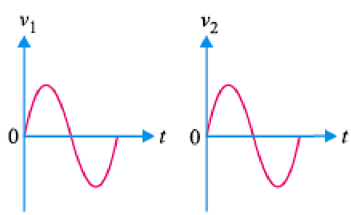
1.2 Common-mode and Differential-mode Signals

1.2.1 Common-mode Operation of DA

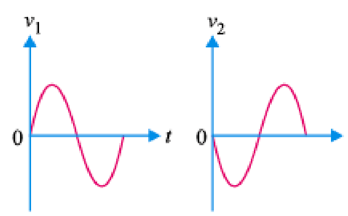
When the input signals to a DA are in phase and exactly equal in amplitude, they are called common-mode signals. The common-mode signals are rejected (not amplified) by the differential amplifier. It is because a differential amplifier amplifies the difference between the two signals (v_1–v_2) and for common-mode signals, this difference is zero. Note that for common-mode operations, $v_1 = v_2$

1.2.2 Differential-mode signals

When the input signals to a DA are 180^0 out of phase and exactly equal in amplitude, they are called differential-mode signals. The differential-mode signals are amplified by the differential amplifier. It is because the difference in the signals is twice the value of each signal.



Common-mode signals



Differential-mode signals

1.3 Common Mode Rejection Ratio - CMRR

It is important to note that common-mode signals are rejected by DA. This action is called **common-mode rejection**. Most of noises and other unwanted signals are common-mode signals. When these unwanted signals appear on the inputs of a DA, they are virtually eliminated on the output.

The voltage gain of a DA operating in differential mode is called **differential-mode voltage gain** and is denoted by A_{DM}. The voltage gain of DA operating in common-mode is called **common-mode voltage gain** and is denoted by A_{CM}. Ideally, a DA provides a very high voltage gain for differential-mode signals and zero gain for common-mode signals. However, practically, differential amplifiers do exhibit a very small common-mode gain (usually much less than 1) while providing a high differential voltage gain (usually several thousands). The higher the differential gain w.r.t. the common-mode gain, the better the performance of the DA in terms of rejection of common-mode signals.

Common Mode Rejection Ration - CMRR is defined as the ratio of differential-mode voltage gain to common-mode voltage gain ,

$$CMRR = \frac{A_{DM}}{A_{CM}}$$

The CMRR is usually expressed in decibels (dB). The decibel measure for CMRR is given by

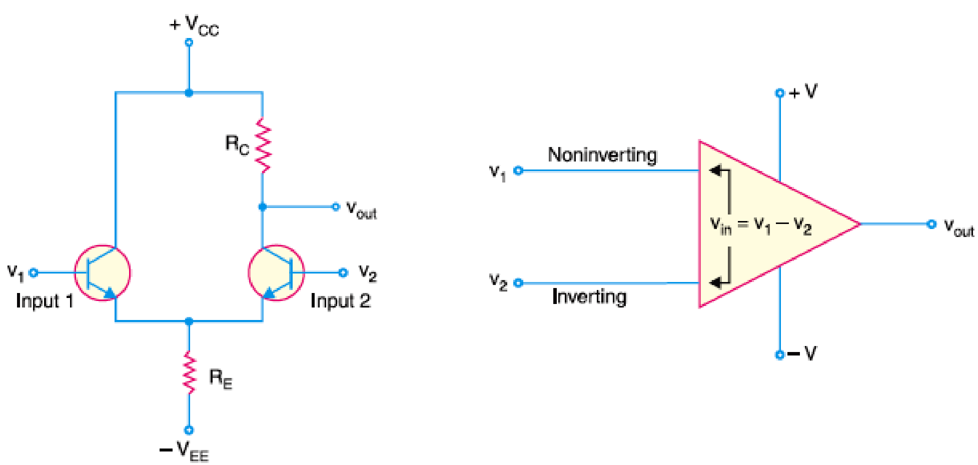
$$CMRR_{dB} = 20\log_{10}\frac{A_{DM}}{A_{CM}}$$

The CMRR is the ability of a DA to reject the common-mode signals. The larger the CMRR, the better the DA is at eliminating common-mode signals.

For good practical opamps, CMRR is about 10^7 or 140 dB. For ideal opamps, it is infinity.

1.4 Overview of Differential Amplifier

Fig. shows double-ended input and single-ended output differential amplifier (DA). In other words, there are two input signals and one output signal. When input signal v_1 (input 1) is applied, the output signal is in phase with the input signal i.e., there is no phase shift in the output signal. For this reason, input signal v_1 is called **non-inverting input**. When input signal v_2 (input 2) is applied, the output signal is 180^0 out of phase with the input signal. For this reason, input signal v_2 is called **inverting input**.



The differential amplifier amplifies the difference between the two input voltages. The difference between the input voltages is $v_{in} = v_1 - v_2$ i.e., where v_1 = the voltage applied to the non-inverting input, v_2 = the voltage applied to the inverting input, v_in = the difference voltage that will be amplified. It is important to remember that the differential amplifier is amplifying the difference between the input terminal voltages.

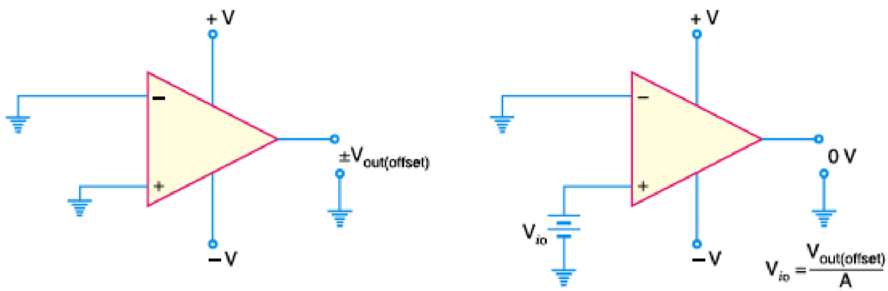
2 Offset parameters

Our discussion on the differential amplifier (DA) has been based on the assumption that the transistors are perfectly matched i.e., they have exactly the same electrical characteristics. In practice, this cannot happen. There will always be some difference between the characteristics of the two transistors. This leads us to the following two parameters of DA (or OP– amp)

2.1 Output Offset Voltage

Even though the transistors in the differential amplifier are very closely matched, there are some differences in their electrical characteristics. One of these differences is found in the values of V_{BE} for the twso transistors. When $V_{BE1} \neq V_{BE2}$, an imbalance is created in the differential amplifier. The DA (or OP-amp) may show some voltage at the output even when the voltage applied between two input terminals is zero. This is called **output offset voltage**. Inputs of DA grounded, the output shows a measurable voltage. This voltage is a result of the imbalance in the differential amplifier, which causes one of the transistors to conduct harder than the other.

There are several methods that may be used to eliminate output offset voltage. One of these is to apply an input offset voltage between the input terminals of DA (or OP- amp) so as to make output $0V$.



2.2 Input Offset Current

When the output offset voltage of a DA (or OP- amp) is eliminated, there will be a slight difference between the input currents to the non-inverting and inverting inputs of the device. This slight difference in input currents is called input offset current and is caused by a beta (β) mismatch between the transistors in the differential amplifier. Let I_{B1} and I_{B2} be the two d.c. base currents. Then

$$I_{in-offset} = I_{B1} - I_{B2}$$

The difference in the base currents indicates how closely matched the transistors are. If the transistors are identical, the input offset current is zero because both base currents will be equal. But in practice, the two transistors are different and the two base currents are not equal.

2.3 Input Bias Current (μA

The inputs to an OP- amp require some amount of d.c. biasing current for the transistors in the differential amplifier. The input bias current is defined as the average of the two d.c. base currents

Let I_{B1} and I_{B2} be the two d.c. base currents. Then

$$I_{in-bias} = \frac{I_{B1} + I_{B2}}{2}$$

The fact that both transistors in the differential amplifier require an input biasing current leads to the following operating restriction : An OP-amp will not work if either of its inputs is open. The open circuit would not allow the d.c. biasing current required for the operation of the differential amplifier (The transistor associated with the inverting input would work but not the one associated with the non-inverting input). Since the differential amplifier would not work, the overall OP-amp circuit would not work. Thus an input bias current path must always be provided for both OP-amp inputs.

Op-amp

2.4 Important properties

1. An operational amplifier is a multistage amplifier. The input stage of an OP-amp is a differential amplifier stage.
2. An inverting input and a non-inverting input.
3. A high input impedance (usually assumed infinite) at both inputs.
4. A low output impedance ($< 200\Omega$).
5. A large open-loop voltage gain, typically 10^5.
6. The voltage gain remains constant over a wide frequency range.
7. Very large CMRR ($> 90\ dB$).

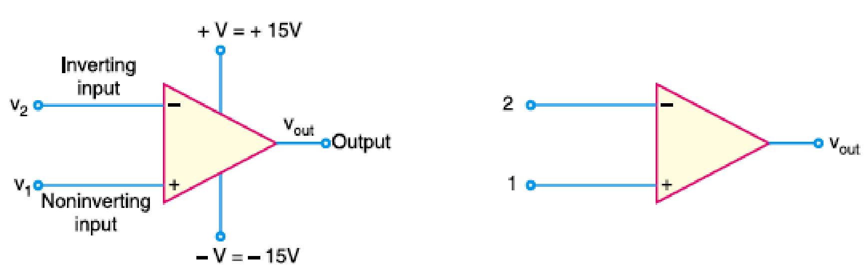
Voltage gain of OP-amp. The maximum possible voltage gain from a given OP-amp is called open-loop voltage gain and is denoted by the symbol A_{OL}. The value of A_{OL} for an OP-amp is generally greater than 10,000. The term open-loop indicates a circuit condition where there is no feedback path from the output to the input of OP-amp. The OP-amps are almost always operated with negative feedback i.e., a part of the output signal is fed back in phase opposition to the input.

The supply voltages for an OP-amp are normally equal in magnitude and opposite in sign e.g., $\pm 15V, \pm 12V$. These supply voltages determine the limits of output voltage of OP-amp. These limits, known as **saturation voltages**, are generally given by

$$+V_{sat} = +V_{supply} - 2V$$
$$-V_{sat} = -V_{supply} + 2V$$

2.5 Schematic Symbol

Fig. shows the schematic symbol of an operational amplifier. The basic operational amplifier has five terminals - two terminals for supply voltages +V and –V; two input terminals (inverting input and non-inverting input) and one output terminal. Two other terminals, the offset null terminals, are used to ensure zero output when the two inputs are equal. These are normally used when small d.c. signals are involved.



2.6 Slew Rate

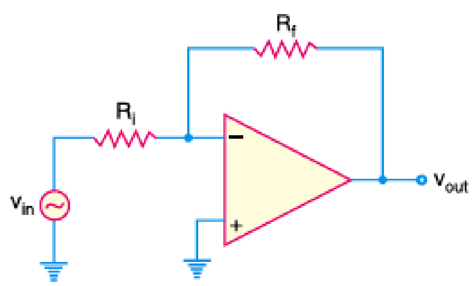
The slew rate of an OP-amp is a measure of how fast the output voltage can change and is measured in volts per microsecond ($V/\mu s$). If the slew rate of an OP-amp is 0.5V/μs, it means that the output from the amplifier can change by 0.5 V every μs. Since frequency is a function of time, the slew rate can be used to determine the maximum operating frequency of the OP-amp as follows: Maximum operating frequency,

$$f_{max} = Slew\ rate/(2\pi V_m)$$

Here V_m is the peak output voltage.

2.7 OP-Amp with Negative Feedback

An OP-amp is almost always operated with negative feedback i.e., a part of the output is fed back in phase opposition to the input. The reason is simple. The open-loop voltage gain of an OP-amp is very high (usually greater than 100,000). Therefore, an extremely small input voltage drives the OP-amp into its saturated output stage.With negative feedback, the voltage gain (A_{CL}) can be reduced and controlled so that OP-amp can function as a linear amplifier. In addition to providing a controlled and stable gain, negative feedback also provides for control of the input and output impedances and amplifier bandwidth.



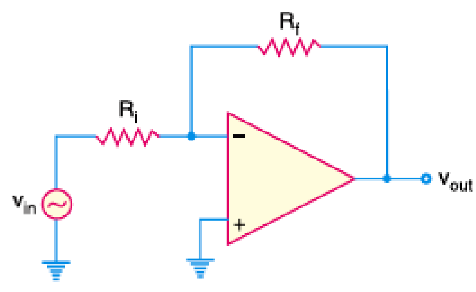
	Voltage gain	Input Z	Output Z	Bandwidth
Without negative feedback	A_{OL} is too high for linear amplifier applications	Relatively high	Relatively low	Relatively narrow
With negative feedback	A_{CL} is set by the feedback circuit to desired value	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

3 Applications of op-amp

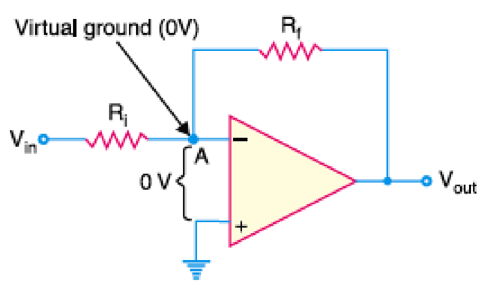
The operational amplifiers have many practical applications. The OP-amp can be connected in a large number of circuits to provide various operating characteristics.

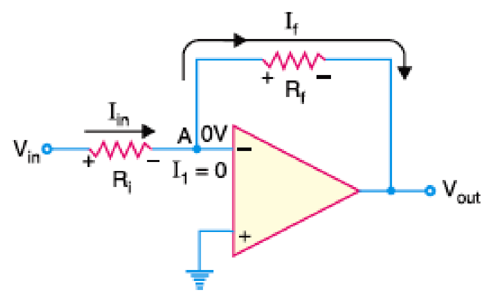
3.1 Inverting Amplifier

An Operational amplifier can be operated as an inverting amplifier. An input signal v_{in} is applied through input resistor R_1 to the minus input (inverting input). The output is fed back to the same minus input through feedback resistor R_f. The plus input (non-inverting input) is grounded. Note that the resistor Rf provides the negative feedback. Since the input signal is applied to the inverting input (–), the output will be inverted (i.e. 180^0 out of phase) as compared to the input. Hence the name **inverting amplifier**.



An OP-amp has an infinite input impedance. This means that there is zero current at the inverting input. If there is zero current through the input impedance, then there must be no voltage drop between the inverting and non-inverting inputs. This means that voltage at the inverting input (–) is zero (point A) because the other input (+) is grounded. The 0V at the inverting input terminal (point A) is referred to as **virtual ground**. This condition is illustrated in Fig. The point A is said to be at virtual ground because it is at 0V but is not physically connected to the ground.





The current I_1 to the inverting input is zero. Therefore, current I_{in} flowing through R_1 entirely flows through feedback resistor R_f. In other words, $I_f = I_{in}$.

$$I_{in} = \frac{V_{in} - V_A}{R_1} = \frac{V_{in} - 0}{R_1} = \frac{V_{in}}{R_1}$$

$$I_f = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = -\frac{V_{out}}{R_f}$$

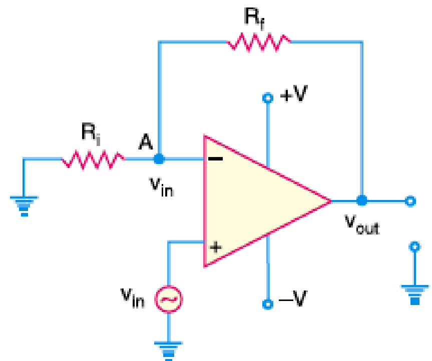
$$\frac{V_{out}}{R_f} = -\frac{V_{in}}{R_1}$$

$$A_{CL} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$$

The negative sign indicates that output signal is inverted as compared to the input signal. The closed-loop voltage gain (A_{CL}) of an inverting amplifier is the ratio of the feedback resistance Rf to the input resistance R_1. The closed-loop voltage gain is independent of the OP-amp's internal open-loop voltage gain. Thus the negative feedback stabilises the voltage gain.

3.2 Non-inverting Amplifier

There are times when we wish to have an output signal of the same polarity as the input signal. In this case, the OP-amp is connected as non-inverting amplifier as shown in Fig. The input signal is applied to the non-inverting input (+). The output is applied back to the input through the feedback circuit formed by feedback resistor R_f and input resistance R_1. Note that resistors R_f and R_1 form a voltage divide at the inverting input (–). This produces negative feedback in the circuit. R_1 is grounded. Since the input signal is applied to the non-inverting input (+), the output signal will be non-inverted i.e., the output signal will be in phase with the input



If we assume that we are not at saturation, the potential at point A is the same as V_{in}. Since the input impedance of OP-amp is very high, all of the current that flows through R_f also flows through R_1.

Current through R_1 = Current through R_f

$$\begin{aligned}\frac{V_{in}-0}{R_1} &= \frac{V_{out}-V_{in}}{R_f}\\ \frac{V_{out}}{V_{in}} &= \frac{R_f+R_1}{R_1}\\ A_{CL} &= 1+\frac{R_f}{R_1}\end{aligned}$$

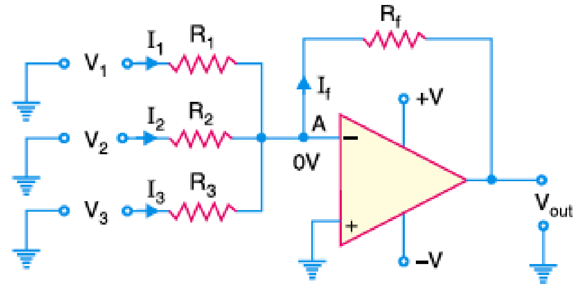
The voltage gain is positive. This is not surprising because output signal is in phase with the input signal. The voltage gain of a non-inverting amplifier will always be greater than the gain of an equivalent inverting amplifier by a value of 1

3.3 Summing amplifier

A summing amplifier is an inverted OP-amp that can accept two or more inputs. The output voltage of a summing amplifier is proportional to the negative of the algebraic sum of its input voltages. Hence the name summing amplifier.

Figure shows a three-input summing amplifier but any number of inputs can be used. Three voltages V_1, V_2 and V_3 are applied to the inputs and produce currents I_1, I_2 and I_3. Using the concepts of infinite impedance and virtual ground, we can see that inverting input of the OP-amp is at virtual ground (0V) and there is no current to the input. This means that the three input currents I_1, I_2 and I_3 combine at the summing point A and form the total current (I_f) which goes through R_f

$$I_f = I_1 + I_2 + I_3$$



When all the three inputs are applied, the output voltage is Output voltage,

$$V_{out} = -I_f R_f = -R_f(I_1 + I_2 + I_3)$$

$$V_{out} = -I_f R_f = -R_f(V_1/R_1 + V_2/R_2 + V_3/R_3)$$

If $R_1 = R_2 = R_3 = R$, then

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3)$$

Thus the output voltage is proportional to the algebraic sum of the input voltages (of course neglecting negative sign). An interesting case results when the gain of the amplifier is unity. In that case, $R_f = R_1 = R_2 = R_3$ and output voltage is

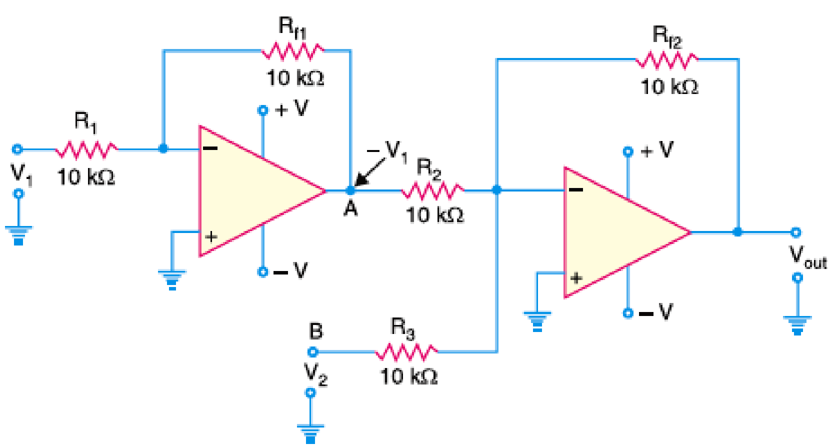
$$V_{out} = -(V_1 + V_2 + V_3)$$

Thus, when the gain of summing amplifier is unity, the output voltage is the algebraic sum of the input voltages.

By proper modifications, a summing amplifier can be made to perform many useful functions. There are a number of applications of summing amplifiers like averaging amplifier, subtractor etc.

3.4 Difference amplifier

By proper modifications, a summing amplifier can be made to subtraction. summing amplifier can be used to provide an output voltage that is equal to the difference of two voltages. Such a circuit is called a subtractor.



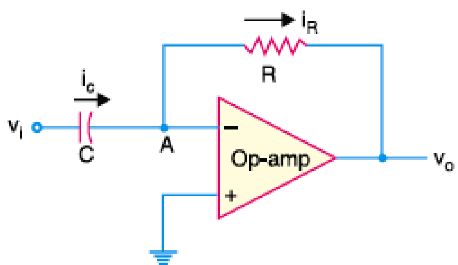
The circuit will provide an output voltage that is equal to the difference between V_1 and V_2. The voltage V_1 is applied to a standard inverting amplifier that has unity gain. Because of this, the output from the inverting amplifier will be equal to $-V_1$. This output is then applied to the summing amplifier (also having unity gain) along with V_2. Thus output from second OP-amp is given by;

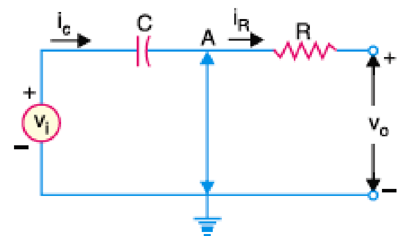
$$V_{out} = -(-V_1 + V_2) = V_1 - V_2$$

It may be noted that the gain of the second stage in the subtractor can be varied to provide an output that is proportional to (rather than equal to) the difference between the input voltages. However, if the circuit is to act as a subtractor, the input inverting amplifier must have unity gain. Otherwise, the output will not be proportional to the true difference between V_1 and V_2.

3.5 Differentiator

A circuit that performs the mathematical differentiation of input signal is called a differentiator. The output of a differentiator is proportional to the rate of change of its input signal. Its important application is to produce a rectangular output from a ramp input. Fig. shows the circuit of OP-amp differentiator. It consists of an OP-amp, an input capacitor C and feedback resistor R. Note how the placement of the capacitor and resistor differs from the integrator. The capacitor is now the input element.





Because of virtual ground and infinite impedance of OP-amp, all the input current i_c flows through the feedback resistor R i.e. $i_c = i_R$.

$$\begin{aligned} i_c &= i_R \\ \frac{d}{dt}v_c = \frac{d}{dt}(v_i - 0) &= -\frac{v_o}{R} \\ v_o &= -RC\frac{d}{dt}(v_i) \end{aligned}$$

Equation shows that output is the differentiation of the input with an inversion and scale multiplier of RC. If the input voltage is constant, dv_i/dt is zero and the output voltage is zero. The faster the input voltage changes, the larger the magnitude of the output voltage.

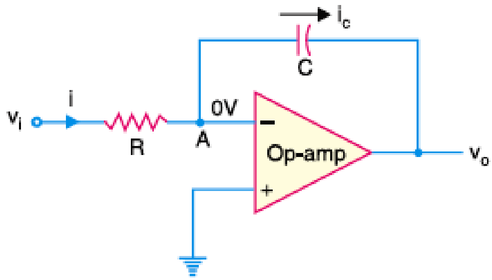
For a square wave input, output will be in the form of spike.

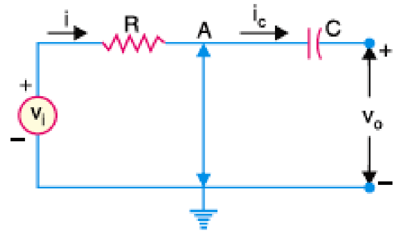
3.6 Integrator

A circuit that performs the mathematical integration of input signal is called an integrator. The output of an integrator is proportional to the area of the input waveform over a period of time.

The most popular application of an integrator is to produce a ramp output voltage (i.e. a linearly increasing or decreasing voltage). Fig. shows the circuit of an OP-amp integrator. It consists of an

OP-amp, input resistor R and feedback capacitor C. The feedback component is a capacitor instead of a resistor.





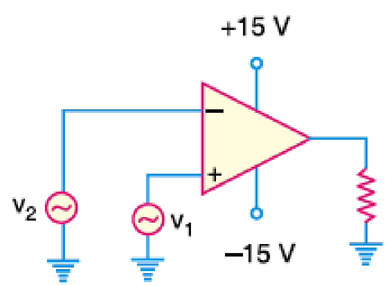
Because of virtual ground and infinite impedance of OP-amp, all the input current i_c flows through the feedback resistor R i.e. $i_c = i$.

$$\begin{aligned} i_c &= i \\ -C\frac{d}{dt}v_c = C\frac{d}{dt}(0 - v_o) &= \frac{v_i}{R} \\ v_o &= -\frac{1}{RC}\int_0^t v_i dt \end{aligned}$$

Eq. shows that the output is the integral of the input with an inversion and scale multiplier of $1/RC$. For a square wave input, the ouput will be a ramp function.

3.7 Comparator

Often we want to compare one voltage to another to see which is larger. In this situation, a comparator may be used. A comparator is an OP-amp circuit without negative feedback and takes advantage of very high open-loop voltage gain of OP-amp. A comparator has two input voltages (noninverting and inverting) and one output voltage. Because of the high open-loop voltage gain of an OP-amp, a very small difference voltage between the two inputs drives the amplifier to saturation.



A very small differential input voltage will drive the OP-amp to saturation. This is the key point in the working of comparator. Fig. illustrates the action of a comparator. The input voltages are v1 (signal) and v2 (reference voltage). If the differential input is positive, the circuit is driven to saturation and output goes to maximum positive value (+Vsat = + 13V). Reverse happens when the differential input goes negative i.e. now output is maximum negative (– Vsat = – 13V). This circuit is called comparator because it compares v1 to v2 to produce a saturated positive or negative output voltage. Note that output voltage rapidly changes from – 13V to + 13V and vice-versa.

A comparator uses no feedback so that the voltage gain is equal to the open-loop voltage gain (A_{OL}) of OP-amp. It is operated in a non-linear mode.

A comparator can be used to produce a square wave output from a sine wave input. When one input of a comparator is connected to ground, it is known as zero-crossing detector because the output changes when the input crosses 0 V. When a comparator is used to compare a signal amplitude to a fixed d.c. level (reference voltage), the circuit is referred to as a level detector.

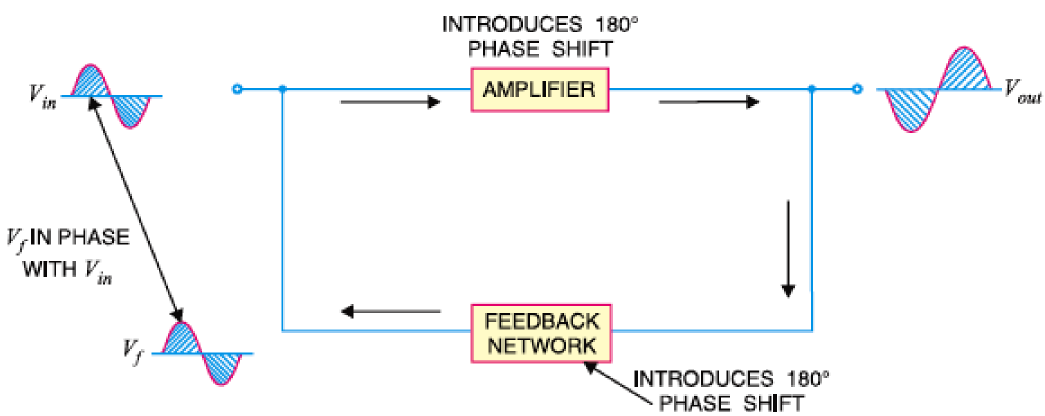
4 Concept of feedback mechanism

The process of injecting a fraction of output energy of some device back to the input is known as feedback.

Feedback has been found very useful in reducing noise in amplifiers and making amplifier operation stable. Depending upon whether the feedback energy aids or opposes the input signal, there are two basic types of feedback in amplifiers viz positive feedback and negative feedback.

4.1 Positive feedback

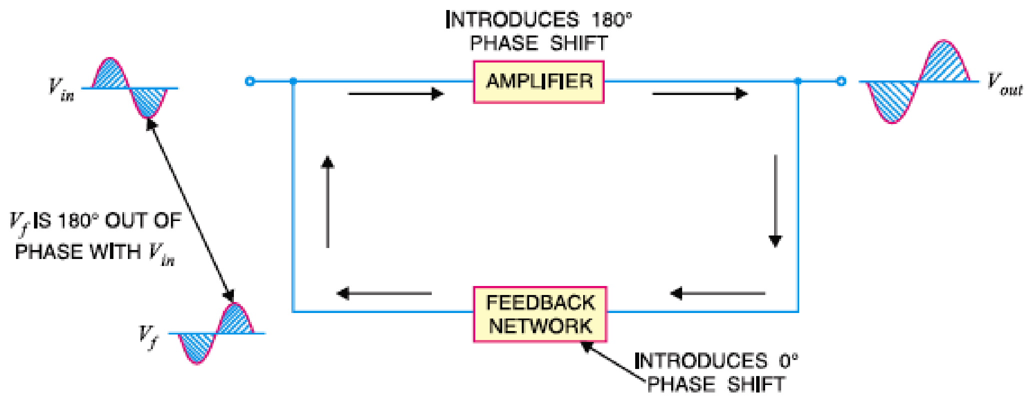
When the feedback energy (voltage or current) is in phase with the input signal and thus aids it, it is called positive feedback. Both amplifier and feedback network introduce a phase shift of 180^0. The result is a 360^0 phase shift around the loop, causing the feedback voltage V_f to be in phase with the input signal V_{in}.



The positive feedback increases the gain of the amplifier. However, it has the disadvantages of increased distortion and instability. Therefore, positive feedback is seldom employed in amplifiers. One important use of positive feedback is in **oscillators**. As we shall see in the next chapter, if positive feedback is sufficiently large, it leads to oscillations. An oscillator is a device that converts d.c. power into a.c. power of any desired frequency.

4.2 Negative feedback

When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called negative feedback. The amplifier introduces a phase shift of 180^0 into the circuit while the feedback network is so designed that it introduces no phase shift (i.e., 0^0 phase shift). The result is that the feedback voltage V_f is 180^0 out of phase with the input signal V_{in}



Negative feedback reduces the gain of the amplifier. However, the advantages of negative feedback are: reduction in distortion, stability in gain, increased bandwidth and improved input and output impedances. It is due to these advantages that negative feedback is frequently employed in **amplifiers**.

5 Oscillators

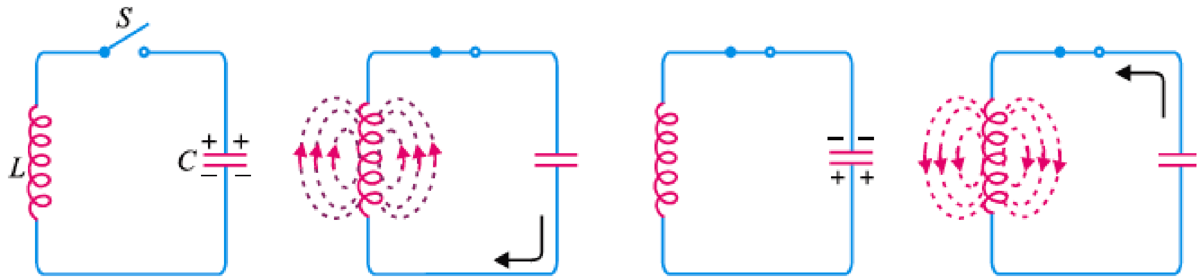
An electronic device that generates sinusoidal oscillations of desired frequency is known as a sinusoidal oscillator.

An oscillator receives d.c. energy and changes it into a.c. energy of desired frequency. The frequency of oscillations depends upon the constants of the device. Although an alternator produces sinusoidal oscillations of 50Hz, it cannot be called an oscillator. Firstly, an alternator is a mechanical device having rotating parts whereas an oscillator is a non-rotating electronic device. Secondly, an alternator converts mechanical energy into a.c. energy while an oscillator converts d.c. energy into a.c. energy. Thirdly, an alternator cannot produce high frequency oscillations whereas an oscillator can produce oscillations ranging from a few Hz to several MHz.

Although oscillations can be produced by mechanical devices (e.g. alternators), but electronic oscillators have the following advantages :
(i) An oscillator is a non-rotating device. Consequently, there is little wear and tear and hence longer life.
(ii) Due to the absence of moving parts, the operation of an oscillator is quite silent.
(iii) An oscillator can produce waves from small (20 Hz) to extremely high frequencies (¿ 100 MHz).
(iv) The frequency of oscillations can be easily changed when desired.
(v) It has good frequency stability i.e. frequency once set remains constant for a considerable period of time.
(vi) It has very high efficiency.

5.1 Tank Circuit

A circuit which produces electrical oscillations of any desired frequency is known as an oscillatory circuit or tank circuit. A simple oscillatory circuit consists of a capacitor (C) and inductance coil (L) in parallel as shown in Fig. This electrical system can produce electrical oscillations of frequency determined by the values of L and C.



The sequence of charge and discharge results in alternating motion of electrons or an oscillating current. The energy is alternately stored in the electric field of the capacitor (C) and the magnetic field of the inductance coil (L). This interchange of energy between L and C is repeated over and again resulting in the production of oscillations.

If there were no losses in the tank circuit to consume the energy, the interchange of energy between L and C would continue indefinitely. In a practical tank circuit, there are resistive and radiation losses in the coil and dielectric losses in the capacitor. During each cycle, a small part of the originally imparted energy is used up to overcome these losses. The result is that the amplitude of oscillating current decreases gradually and eventually it becomes zero when all the energy is consumed as losses. Therefore, the tank circuit by itself will produce **damped oscillations**.

The frequency of oscillations in the tank circuit is determined by the constants of the circuit viz L and C. The actual frequency of oscillations is the resonant frequency (or natural frequency) of the tank circuit given by :

$$f = \frac{1}{2\pi\sqrt{LC}}$$

5.2 Undamped Oscillations

In order to make the oscillations in the tank circuit undamped, it is necessary to supply correct amount of energy to the tank circuit at the proper time intervals to meet the losses. Any energy which would be applied to the circuit must have a polarity conforming to the existing polarity at the instant of application of energy. If the applied energy is of opposite polarity, it would oppose the energy in the tank circuit, causing stoppage of oscillations. Therefore, in order to make the oscillations in the tank circuit undamped, the following conditions must be fulfilled :

(i)The amount of energy supplied should be such so as to meet the losses in the tank circuit and the a.c. energy removed from the circuit by the load.
(ii) The applied energy should have the same frequency as that of the oscillations in the tank circuit.
(iii) The applied energy should be in phase with the oscillations set up in the tank circuit i.e. it should aid the tank circuit oscillations.

6 Transistor Oscillator

A transistor amplifier with proper positive feedback can act as an oscillator i.e., it can generate oscillations without any external signal source.

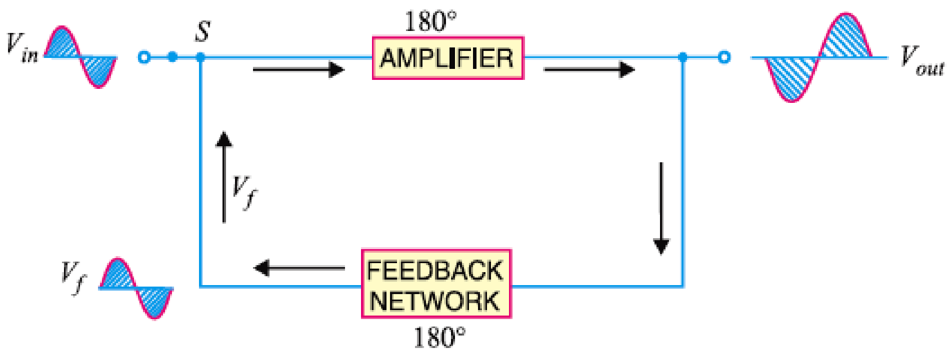
The amplifier will produce sinusoidal output with no external signal source.

- A transistor amplifier with proper positive feedback will work as an oscillator.
- The circuit needs only a quick trigger signal to start the oscillations. Once the oscillations have started, no external signal source is needed.
- In order to get continuous undamped output from the circuit, the following condition must be met :

$$m_v A_v = 1$$

where A_v = voltage gain of amplifier without feedback, m_v = feedback fraction

This relation is called **Barkhausen criterion**



6.1 Barkhausen Criterion

Barkhausen criterion is that in order to produce continuous undamped oscillations at the output of an amplifier, the positive feedback should be such that :

$$m_v A_v = 1$$

Once this condition is set in the positive feedback amplifier, continuous undamped oscillations can be obtained at the output immediately after connecting the necessary power supplies.

The voltage gain of a positive feedback amplifier is given by

$$A_{vf} = \frac{A_v}{1 - m_v A_V}$$

If $m_v A_v = 1$, then $A_{vf} \to \infty$. It means that a vanishing small input voltage would give rise to finite (i.e., a definite amount of) output voltage even when the input signal is zero. Thus once the circuit receives the input trigger, it would become an oscillator, generating oscillations with no external signal source.

6.2 Essentials of Transistor Oscillator

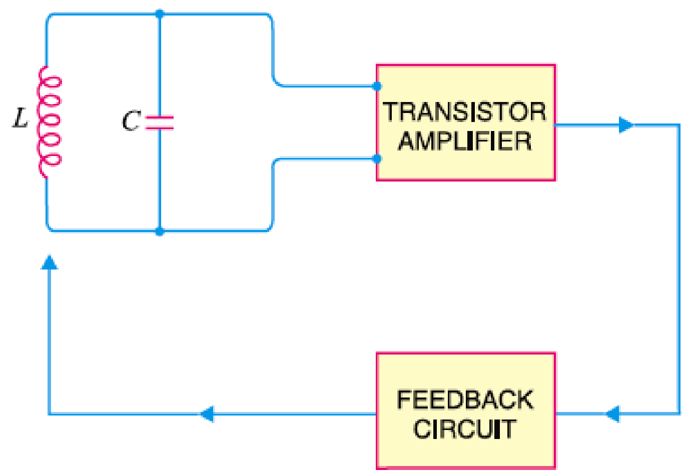
A transistor Oscillator should have

6.2.1 Tank circuit

It consists of inductance coil (L) connected in parallel with capacitor (C). The frequency of oscillations in the circuit depends upon the values of inductance of the coil and capacitance of the capacitor.

6.2.2 Transistor amplifier

The transistor amplifier receives d.c. power from the battery and changes it into a.c. power for supplying to the tank circuit. The oscillations occurring in the tank circuit are applied to the input of the transistor amplifier. Because of the amplifying properties of the transistor, we get increased output of these oscillations. This amplified output of oscillations is due to the d.c. power supplied by the battery. The output of the transistor can be supplied to the tank circuit to meet the losses.



6.2.3 Feedback circuit

The feedback circuit supplies a part of collector energy to the tank circuit in correct phase to aid the oscillations i.e. it provides positive feedback.

7 Different types of transistor oscillators

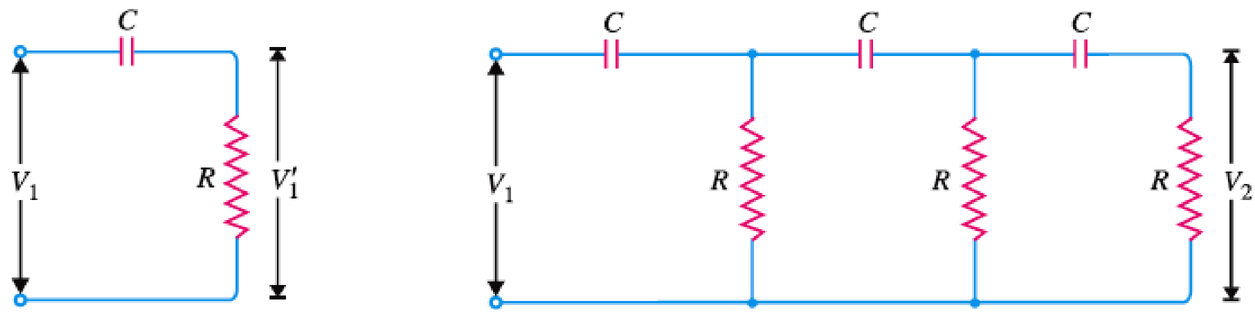
A transistor can work as an oscillator to produce continuous undamped oscillations of any desired frequency if tank and feedback circuits are properly connected to it. All oscillators under different names have similar function i.e., they produce continuous undamped output. However, the major difference between these oscillators lies in the method by which energy is supplied to the tank circuit to meet the losses.

The oscillator circuits employing **L-C elements** have two general drawbacks. Firstly, they suffer from frequency instability and poor waveform. Secondly, they cannot be used for very low frequencies because they become too much bulky and expensive. Good frequency stability and waveform can be obtained from oscillators employing resistive and capacitive elements. Such amplifiers are called **R-C or phase shift oscillators** and have the additional advantage that they can be used for very low frequencies.

7.1 Phase shift oscillator

In a phase shift oscillator, a phase shift of 180^0 is obtained with a phase shift circuit instead of inductive or capacitive coupling. A further phase shift of 180^0 is introduced due to the transistor properties. Thus, energy supplied back to the tank circuit is assured of correct phase.

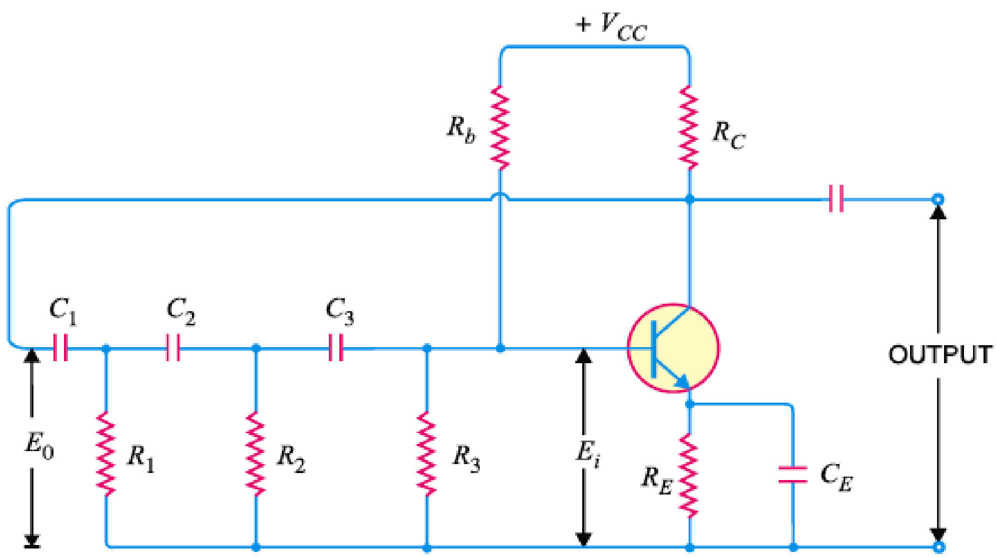
A phase-shift circuit essentially consists of an R-C network. Alternating voltage V_1' across R leads the applied voltage V_1 by ϕ^0. The value of ϕ depends upon the values of R and C. If resistance R is varied, the value of ϕ also changes. If R were reduced to zero, V_1' will lead V_1 by 90^0 i.e. $\phi = 90^0$. However, adjusting R to zero would be impracticable because it would lead to no voltage across R. Therefore, in practice, R is varied to such a value that makes V_1' to lead V_1 by 60^0. In the figure, each section produces a phase shift of 60^0. Consequently, a total phase shift of 180^0 is produced i.e. voltage V_2 leads the voltage V_1 by 180^0.



The following figure shows the circuit of a phase shift oscillator. It consists of a conventional single transistor amplifier and a RC phase shift network. The phase shift network consists of three sections $R_1C_1, R_{2C}2$ and R_3C_3. At some particular frequency f_0, the phase shift in each RC section is 60^0 so that the total phase-shift produced by the RC network is 180^0. The frequency of oscillations is given by

$$f_0 = \frac{1}{2\pi RC\sqrt{6}}$$

with $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$



When the circuit is switched on, it produces oscillations. The output E_0 of the amplifier is fed back to RC feedback network. This network produces a phase shift of 180^0 and a voltage E_i appears at its output which is applied to the transistor amplifier. Obviously, the feedback fraction $m = E_i/E_0$. The feedback phase is correct. A phase shift of 180^0 is produced by the transistor amplifier. A further phase shift of 180^0 is produced by the RC network. As a result, the phase shift around the entire loop is 360^0.

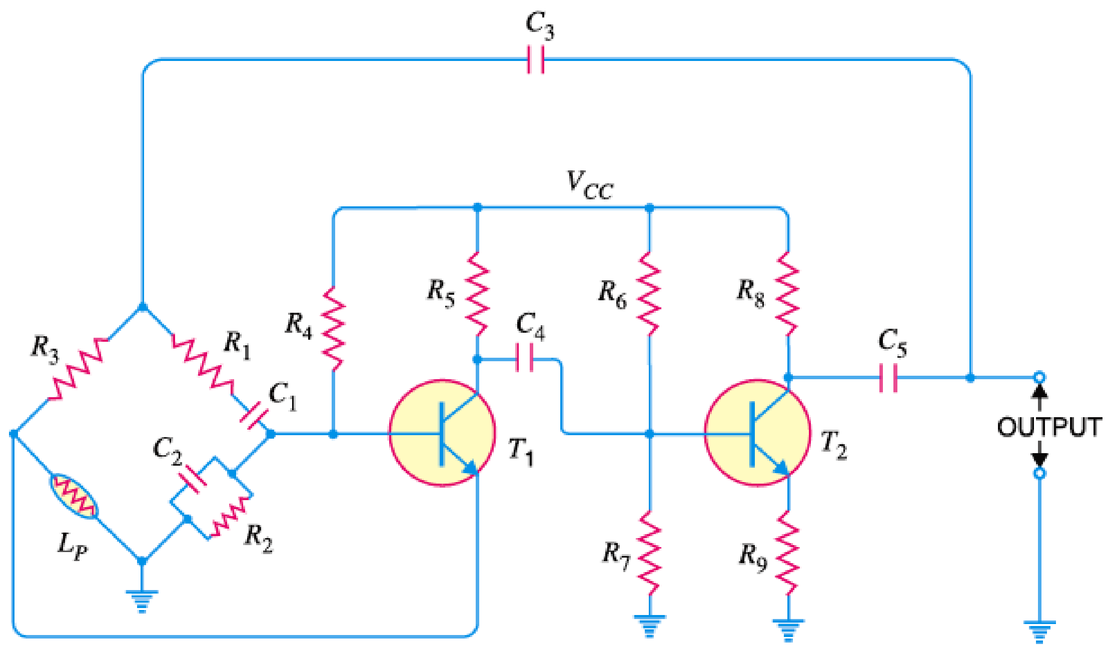
Advantages

(i) It does not require transformers or inductors.

(ii) It can be used to produce very low frequencies.
(iii) The circuit provides good frequency stability.
Disadvantages
(i) It is difficult for the circuit to start oscillations as the feedback is generally small.
(ii) The circuit gives small output.

7.2 Wien Bridge oscillator

The Wien-bridge oscillator is the standard oscillator circuit for all frequencies in the range of 10 Hz to about 1 MHz. It is the most frequently used type of audio oscillator as the output is free from circuit fluctuations and ambient temperature. Fig. shows the circuit of Wien bridge oscillator. It is essentially a two-stage amplifier with R-C bridge circuit. The bridge circuit has the arms R_1C_1, R_3, R_2C_2 and tungsten lamp L_p. Resistances R_3 and L_p are used to stabilise the amplitude of the output. The transistor T1 serves as an oscillator and amplifier while the other transistor T2 serves as an inverter (i.e. to produce a phase shift of 180^0). The circuit uses positive and negative feedbacks.



The positive feedback is through R_1C_1, C_2R_2 to the transistor T1. The negative feedback is through the voltage divider to the input of transistor T2. The frequency of oscillations is determined by the series element R_1C_1 and parallel element R_2C_2 of the bridge.

$$f = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}$$

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

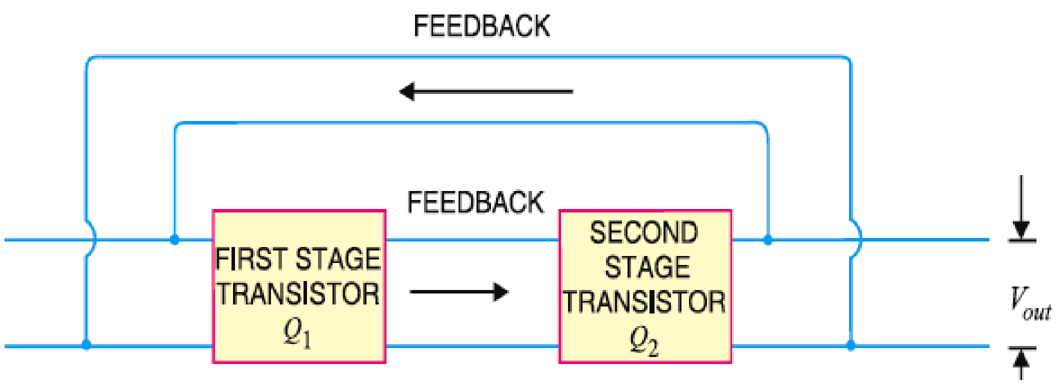
$$f = \frac{1}{2\pi RC}$$

When the circuit is started, bridge circuit produces oscillations. The two transistors produce a total phase shift of 360^0 so that proper positive feedback is ensured. The negative feedback in the circuit ensures constant output. This is achieved by the temperature sensitive tungsten lamp L_p. Its resistance

increases with current. Should the amplitude of output tend to increase, more current would provide more negative feedback. The result is that the output would return to original value. A reverse action would take place if the output tends to decrease.
Advantages
(i) It gives constant output
(ii) The circuit works quite easily
(iii) The overall gain is high because of two transistors
(iv) The frequency of oscillations can be easily changed by using a potentiometer
Disadvantages
(i) The circuit requires two transistors and a large number of components
(ii) It cannot generate very high frequencies

8 Multivibrators

An electronic circuit that generates square waves (or other non-sinusoidals such as rectangular, saw-tooth waves) is known as a multivibrator. The name multivibrator is derived from the fact that a square wave actually consists of a large number of (fourier series analysis) sinusoidals of different frequencies. A multivibrator is a switching circuit which depends for operation on positive feedback. It is basically a two-stage amplifier with output of one fedback to the input of the other.



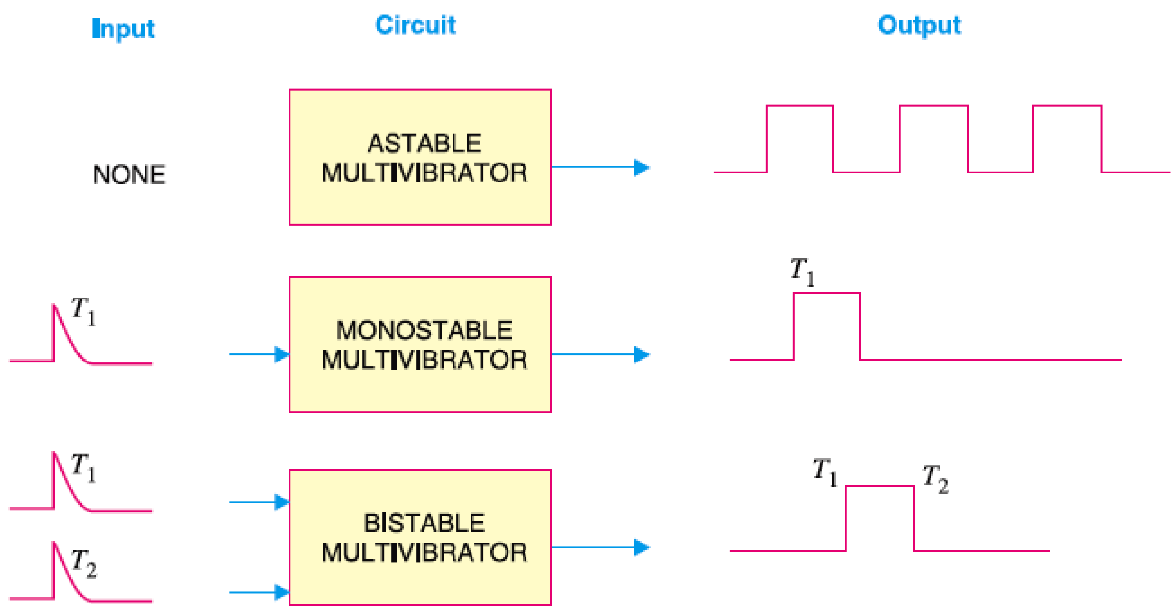
A multivibrator is basically a two-stage amplifier with output of one fedback to the input of the other. At any particular instant, one transistor is ON and the other is OFF. After a certain time depending upon the circuit components, the stages reverse their conditions – the conducting stage suddenly cuts off and the non-conducting stage suddenly starts to conduct.

Depending upon the manner in which the two stages interchange their states, the multivibrators are classified as : **Astable or free running multivibrator, Monostable or one-shot multivibrator and Bi-stable or flip-flop multivibrator**

The astable or free running multivibrator alternates automatically between the two states and remains in each for a time dependent upon the circuit constants. Thus it is just an oscillator since it requires no external pulse for its operation. Of course, it does require a source of d.c. power. Because it continuously produces the square-wave output, it is often referred to as a free running multivibrator.

The monostable or one-shot multivibrator has one state stable and one quasi-stable (i.e. half-stable) state. The application of input pulse triggers the circuit into its quasi-stable state, in which it remains for a period determined by circuit constants. After this period of time, the circuit returns to its initial stable state, the process is repeated upon the application of each trigger pulse. Since the monostable multivibrator produces a single output pulse for each input trigger pulse, it is generally called one-shot multivibrator.

The bistable multivibrator has both the two states stable. It requires the application of an external triggering pulse to change the operation from either one state to the other. Thus one pulse is used to generate half-cycle of square wave and another pulse to generate the next half-cycle of square wave. It is also known as a flip-flop multivibrator because of the two possible states it can assume.



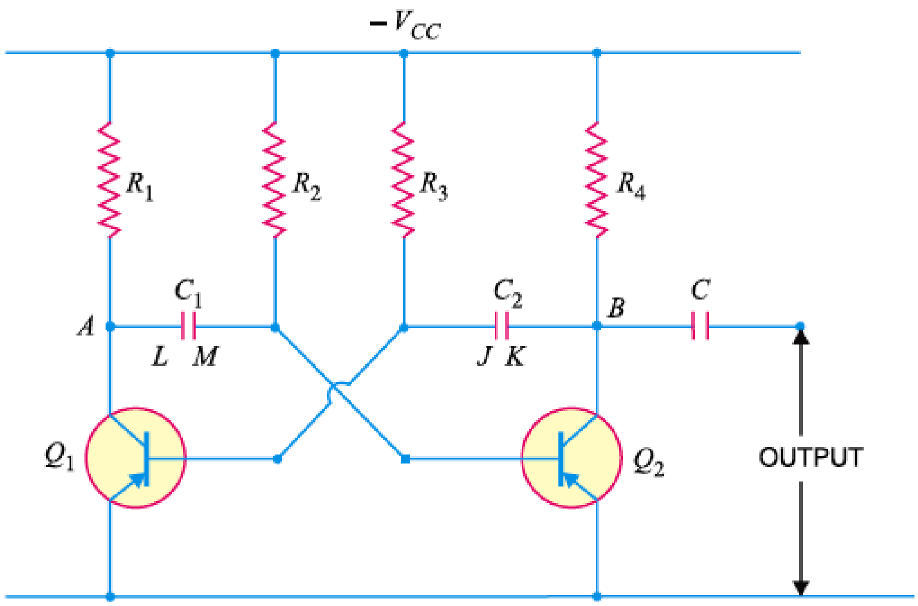
8.1 Transistor Astable Multivibrator

A multivibrator which generates square waves of its own (i.e. without any external triggering pulse) is known as an astable or free running multivibrator.

The astable multivibrator has no stable state. It switches back and forth from one state to the other, remaining in each state for a time determined by circuit constants. In other words, at first one transistor conducts (i.e. ON state) and the other stays in the OFF state for some time. After this period of time, the second transistor is automatically turned ON and the first transistor is turned OFF. Thus the multivibrator will generate a square wave output of its own. The width of the square wave and its frequency will depend upon the circuit constants.

Figure shows the circuit of a typical transistor astable multivibrator using two identical transistors Q_1 and Q_2. The circuit essentially consists of two symmetrical CE amplifier stages, each providing a feedback to the other. Thus collector loads of the two stages are equal i.e. $R_1 = R_4$ and the biasing resistors are also equal i.e. $R_2 = R_3$. The output of transistor Q_1 is coupled to the input of Q_2 through C_1 while the output of Q_2 is fed to the input of Q_1 through C_2. The square wave output can be taken from Q_1 or Q_2.

When V_{CC} is applied, collector currents start flowing in Q_1 and Q_2. In addition, the coupling capacitors C_1 and C_2 also start charging up. As the characteristics of no two transistors (i.e. β, V_{BE}) are exactly alike, therefore, one transistor, say Q_1, will conduct more rapidly than the other. The rising collector current in Q_1 drives its collector more and more positive. The increasing positive output at point A is applied to the base of transistor Q_2 through C1. This establishes a reverse bias on Q_2 and its collector current starts decreasing. As the collector of Q_2 is connected to the base of Q_1 through C_2, therefore, base of Q_1 becomes more negative i.e. Q_1 is more forward biased. This further increases the collector current in Q_1 and causes a further decrease of collector current in Q_2. This series of actions is repeated until the circuit drives Q_1 to saturation and Q_2 to cut off. These actions occur very rapidly and may be considered practically instantaneous. The output of Q_1 (ON state) is approximately zero and that of Q_2 (OFF state) is approximately V_{CC}.



When Q_1 is at saturation and Q_2 is cut off, the full voltage V_{CC} appears across R_1 and voltage across R_4 will be zero. The charges developed across C_1 and C_2 are sufficient to maintain the saturation and cut off conditions at Q_1 and Q_2 respectively. As C_1 discharges, the base bias at Q_2 becomes less positive and at a time determined by R_2 and C_1, forward bias is re-established at Q_2. This causes the collector current to start in Q_2. The increasing positive potential at collector of Q_2 is applied to the base of Q_1 through the capacitor C_2. Hence the base of Q_1 will become more positive i.e. Q_1 is reverse biased. The decrease in collector current in Q_1 sends a negative voltage to the base of Q_2 through C_1, thereby causing further increase in the collector current of Q_2. With this set of actions taking place, Q_2 is quickly driven to saturation and Q_1 to cut off. The period of time during which Q_2 remains at saturation and Q_1 at cut off is determined by C_2 and R_3.

ON or OFF time. The time for which either transistor remains ON or OFF is given by : ON time for Q_1 (or OFF time for Q_2) is

$$T_1 = 0.694 R_2 C_1$$

OFF time for Q_1 (or ON time for Q_2) is

$$T_2 = 0.694 R_3 C_2$$

Total time period of the square wave is

$$T = T_1 + T_2 = 0.694(R_2C_1 + R_3C_2) \approx 1.4RC$$

Frequency of the square wave is

$$\boxed{f = \frac{1}{T} = \frac{1}{1.4RC}}$$

9 Questions

1. What is an opamp ? Why is it called so ?
2. What is a by differential amplifier ?
3. Define the term CMRR
4. What are common mode and differential mode ?
5. Which are the various stages of an opamp ?
6. What are the properties of an opamp ?
7. Define various offset parameters of an opamp
8. Explain the construction and working of
   (a) Inverting and Non-inverting amplifier
   (b) Summing amplifier
   (c) Difference amplifier
   (d) Differentiator
   (e) Integrator
   (f) Comparator
9. Differentiate between positive and negative feedback
10. What is an oscillator ?
11. What is tank circuit ?
12. Explain Barkhausen criterion
13. Explain the construction and working of
    (a) Phase shift oscillator
    (b) Wien bridge oscillator
14. What are the advantages of RC oscillators over LC oscillators ?
15. What are multivibrators ? Why are they called so ? Classify multivibrators
16. Explain the construction and working of an astable multivibrator using transistors