UNIT 2

UNIT 2 FILTERS AND SIGNAL GENERATORS 9 Hrs.

First order and Second order Butterworth filters- low pass, high pass, band pass and band reject filters -RC phase shift, Wien's bridge oscillator- Astable and Monostable multivibrator-Precision half wave and full wave rectifiers.

TABLE OF TOPICS

2.1 ACTIVE FILTERS

FILTERS are circuits used for select signal components of required frequencies and reject other unwanted frequency components. Thus selectivity is one of the main criteria for a filter circuit in communication engineering.

These filters are actually allowing the required frequency bands and attenuate the unwanted frequency bands but they are not adaptive and precise. The allowing band is termed as pass band and attenuating band is termed as stop band. The output gain of the filters in pass band is high and that in stop band is very low (negligible). For ideal filters, pass band gain is infinite and stop band gain is zero. The frequency that acts as a barrier between stop and pass band is termed as cut-off frequency. The design of a filter is based particularly on this cut-off frequency. It is found that the practical value of the cut-off frequency is 3dB less than the maximum frequency allowed.

These filters are considered to be passive when passive components like resistors, capacitors and inductors are used in constructing the circuits. Passive filters are the basic filters used in communication engineering but they are not adaptive and precise. For a good filter, the slope of frequency response plot from pass band to stop band or vice versa should be high. But passive filters sometimes have very low slope for changing input signals and other factors. Even in pass band the gain is not constant but varies. These problems are minimized by using active filters which are adaptive (manage the gain to be constant throughout the pass band and slope to be very high for even a major change in input signals).

Active filters use OP AMP to be adaptive in nature with lager controllable gain value.

Advantages of active filters over passive filters:

1. Reduced size and weight
2. Increased reliability and improved performance
3. Simple design and good voltage gain
4. When fabricated in larger quantities, cheaper than passive filters

Disadvantages of Active Filters:

1. Limited bandwidth only.
2. Quality factor is also limited
3. Require power supply (passive doesn't require power supply)
4. Changes due to environmental factors.

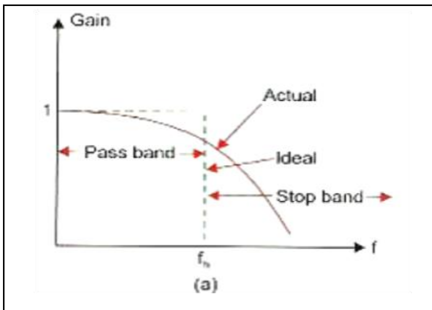
Possible question: *What is an active filter? What are its advantages over passive filters?*

2.1.1 Order of Butterworth filters

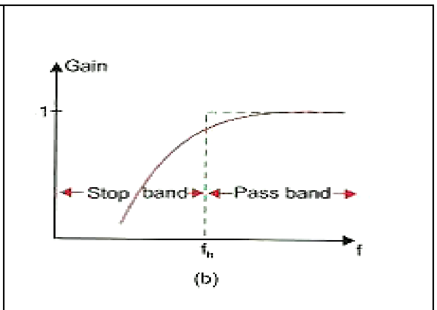
Butterworth filters were designed by a British engineer Stephen Butterworth as a maximally flat-response filter. This filter minimizes ripples and manages to maintain a flat response in pass band.

Order of a filter is the magnitude of voltage transfer function of a filter that decreases by -(20*n)dB/decade as the order 'n' increases in stop band and flat in pass band. This is shown in the fig. 2.1.

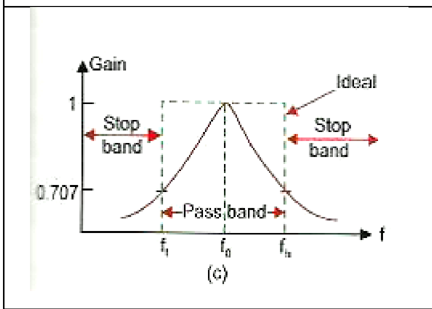
Types of filters according to the response:



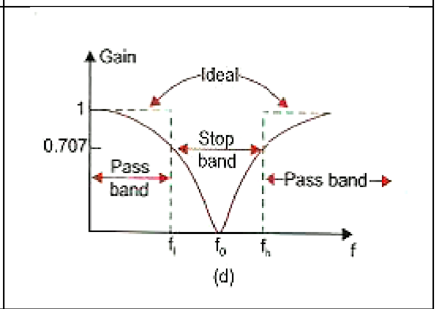
(a). Low pass filter response



(b).High pass filter response



(c). Band pass filter response



(d). Band reject filter response

Fig. 2.1. Filter Responses of all types.

For example, if the order is 50, then the filter response in stop band decreases by -100 dB/decade. So if order increases

1. The magnitude of voltage transfer function in stop band is very high and slope decreases by 20 db/decade.

2. but the circuit complexity increases.

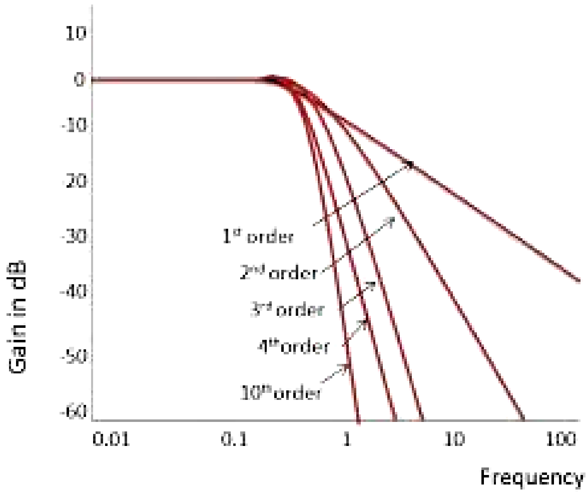


Fig.2.1.1. A Sample Butterworth Filter Response - Order wise

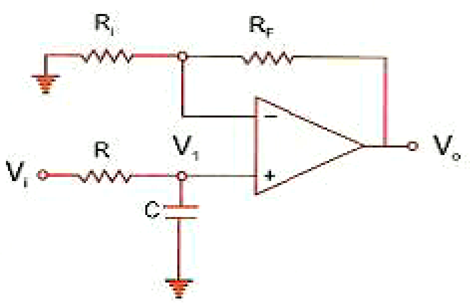
Note: Butterworth filters have flat response in pass bands and decrease in response of -20dB /per decade in pass bands.

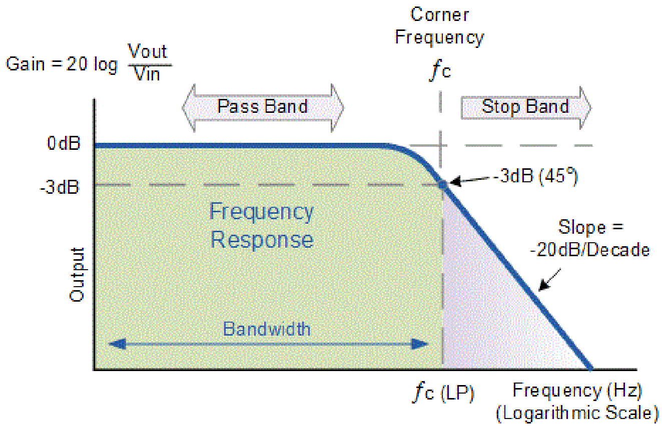
Possible question: *Write short notes on the order of Butterworth filters.*

2.1.1.1. Low Pass Filters

A low pass filter allows low frequencies upto a corner frequency (cut-off frequency) and attenuates (stops) high frequencies above cut-off frequency. This is shown in the frequency response fig. 2.1.1.1.b.

The circuit is a simple non-inverting amplifier, where a RC low pass filter circuit is connected to the input. Capacitor allows high frequencies through it and blocks low frequencies. This characteristic of capacitor is used in these filters.





(a). Filter Circuit ***(b). Filter Response***

Fig. 2.1.1.1. Active Low pass filter- First Order

Here resistor R, smoothens the input signal and the capacitor C allows higher frequencies to reach the ground. Thus high frequency signals never reach the input terminal and only low frequency signal reaches the input terminal.

How corner frequency is obtained?

In the response fig. 2.1.1.1.b., a frequency is noted where the response curve point meets a -3dB line drawn below the maximum gain. The frequency is considered as *corner frequency* (f_C) above which the filter attenuates the input signal and below which it allows the signal.

As shown in the fig. 2.1.1.1.b response -20 dB/decade slope is obtained.

The response analysis shall be analyzed in the following section.

The voltage v_1 across the capacitor C in the s-domain is

$$V_1(s) = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} V_i(s)$$

So,

$$\frac{V_1(s)}{V_i(s)} = \frac{1}{RCs + 1}$$

Where $V(s)$ is the Laplace transform of v in time domain. The closed loop gain A_o of the op-amp is

$$A_o = \frac{V_o(s)}{V_1(s)} = 1 + \frac{R_f}{R_i}$$

So the overall transfer function from above Equations

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{V_o(s)}{V_1(s)} \frac{V_1(s)}{V_i(s)} = \frac{A_o}{RCs + 1}$$

Let

$$\omega_h = \frac{1}{RC}$$

Therfore,

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{A_o}{\frac{s}{\omega_h} + 1} = \frac{A_o \omega_h}{s + \omega_h}$$

This is the standard form of the transfer function of a first order low-pass system.

To determine the frequency response put s=jω in above equation. Thus we get

$$H(j\omega) = \frac{A_o \frac{1}{RC}}{j\omega + \frac{1}{RC}}$$

$$H(j\omega) = \frac{A_o}{j\omega RC + 1}$$

$$H(j\omega) = \frac{A_o}{j\omega RC + 1}$$

$$H(j\omega) = \frac{A_o}{j(\frac{f}{f_h}) + 1}$$

where $f_h = \frac{1}{2\pi RC}$ and $f = \frac{\omega}{2\pi}$

1. At very low frequency, i.e. $\boldsymbol{f \ll f_h}$

$$|H(j\omega)| \cong A_o$$

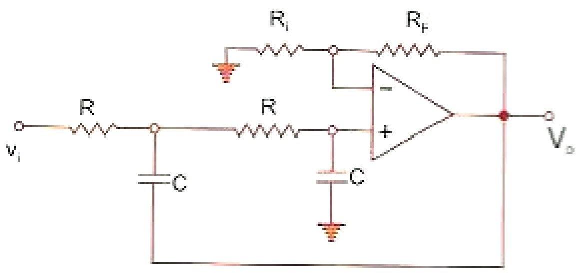
2. At $\boldsymbol{f = f_h}$

$$|H(j\omega)| = \frac{A_o}{\sqrt{2}} = 0.707A_o$$

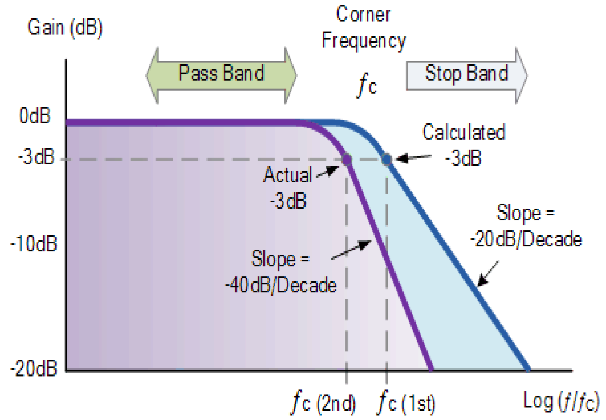
3. At very high frequency, i.e. $\boldsymbol{f \gg f_h}$

$$|H(j\omega)| \ll A_o \cong 0$$

Second order Low pass filter and its response



(c). Filter Circuit



(d). Frequency response

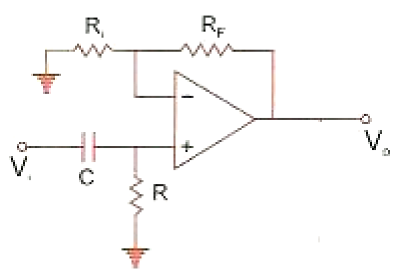
Fig. 2.1.1.1.c & d: Second Order Active Low Pass Filter

With first order circuit, another RC circuit is added as shown in the fig. 2.1.1.1.c and the response is shown in fig. 2.1.1.1.d for second order LPF with a slope of -40 dB/ decade. This is due to the fact that each RC network introduces -20dB decrease in stop band response slope.

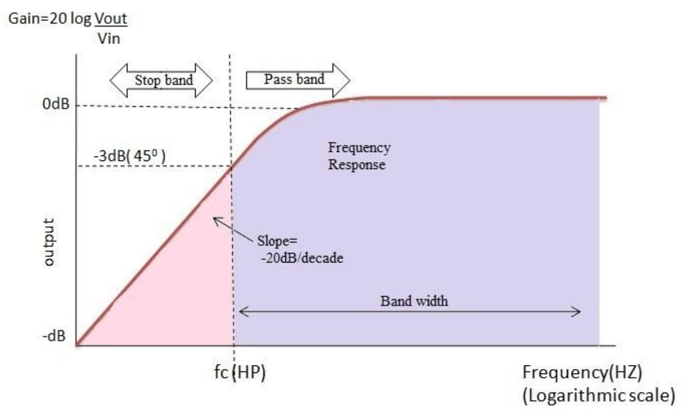
2.1.1.2. High Pass Filters

A high pass filter attenuates low frequencies below corner frequency (cut-off frequency) and allows high frequencies above cut-off frequency. This is shown in the frequency response fig. 2.1.1.2.b.

The circuit is a simple non-inverting amplifier, where a RC low pass filter circuit is connected to the input.



(a). Filter Circuit



(b). Frequency response

Fig. 2.1.1.2. First Order Active High Pass Filter

As shown in the above fig. 2.1.1.2.(a)., Capacitor C blocks low frequency signals below the corner frequency f_c as shown in fig. 2.1.1.2.(b). The response curve increases 20 dB per decade at low frequencies below corner frequencies.

2.1.1.3. Band Pass Filters

A Band pass filter allows a band of frequencies and blocks lower and higher frequencies other than the allowed band as shown in fig. 2.1.1.3.b. As shown in the fig. 2.1.1.3.a, high pass and low pass filters are connected in series.

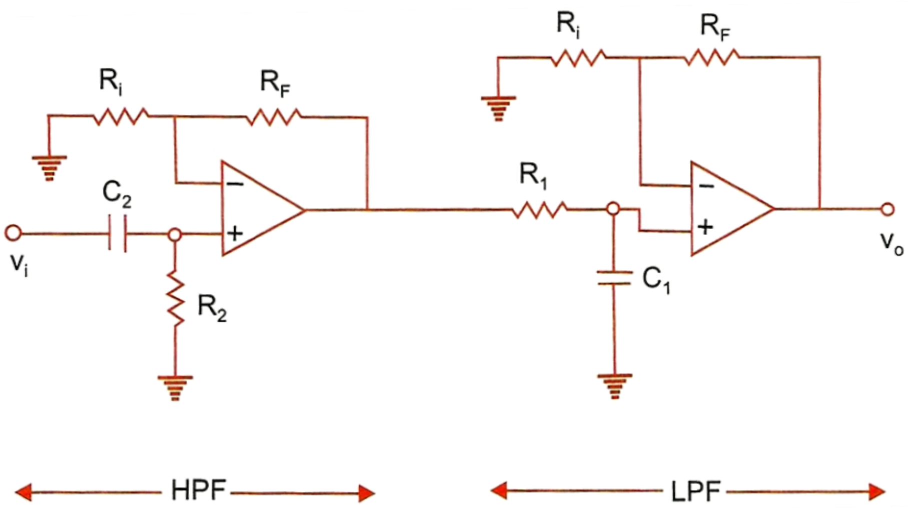


Fig. 2.1.1.3. a. Active Band Pass Filter

The corner frequency of low pass filter f_L is chosen to be lower than that of high pass filter f_H. Thus the difference between f_H and f_L is considered to be the pass band. In low frequency stop band, the response increases 20 dB per decade and in high frequency stop band, the response decreases by 20 dB per decade.

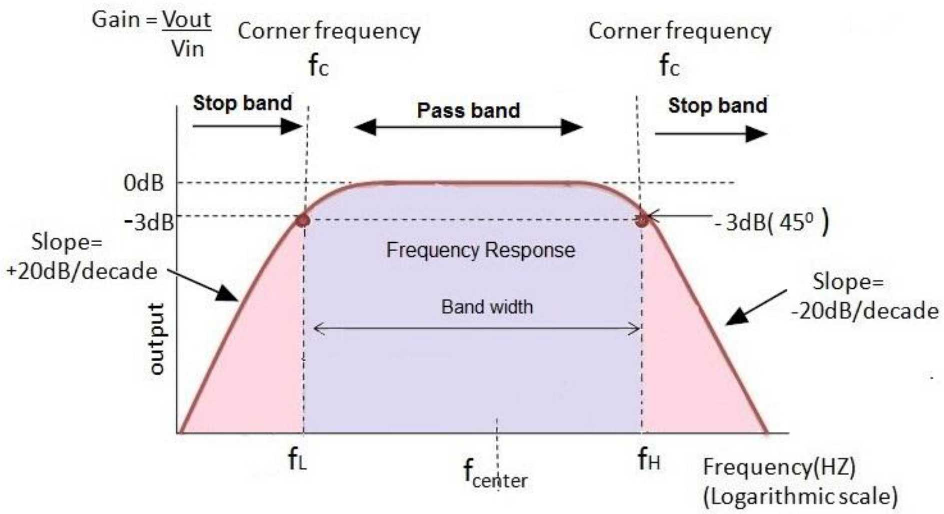


Fig. 2.1.1.3.b. Response of Active Band Pass Filter

2.1.1.4. Band Reject Filters (Notch filter)

A Band pass filter blocks a band of frequencies and allows lower and higher frequencies other than the blocked band as shown in fig. 2.1.1.4.b. As shown in the fig. 2.1.1.4.a, band pass filter is connected to a summer circuit. The input and output of the band pass filter is summed up at the inverting summer input. The bands are inverted by the inverting summer and so pass band of band pass filter becomes stop band and stop bands becomes pass bands. Thus this filter only allows particular band above lower corner frequency f_L and below upper corner frequency f_H.

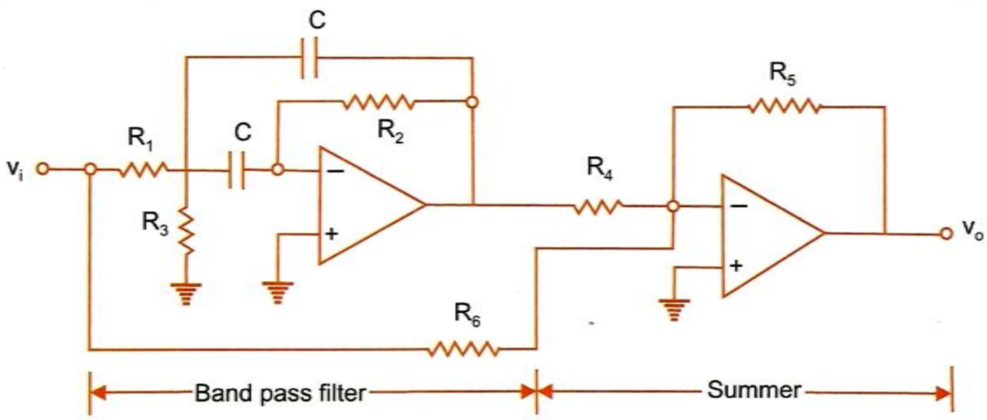


Fig. 2.1.1.4.a. Active Band Reject Filter

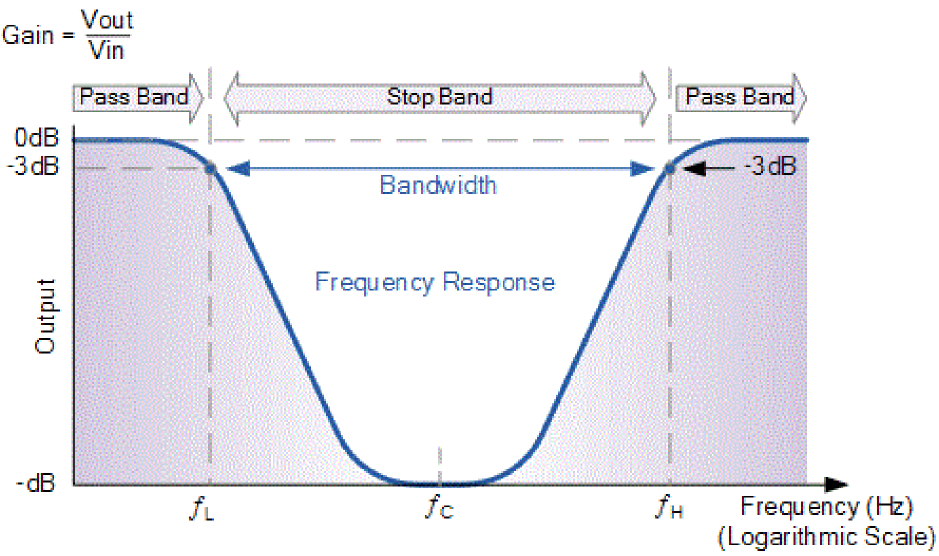


Fig. 2.1.1.4.b. Response of Active Band Reject Filter

Possible questions:

Write briefly about first and second order Butterworth Low-pass filter with neat sketches.

Write briefly about first and second order Butterworth high-pass filter with neat sketches.

Write briefly about first order Butterworth band-pass filter with neat sketches.

Write briefly about first order Butterworth band-reject filter with neat sketches. .

Write briefly about Notch filter with neat sketches.

2.2 OP-AMP OSCILLATORS

In electronics, oscillators are circuits that generate sinusoidal or non-sinusoidal waveforms used as reference signals in communication engineering. The non-sinusoidal waveforms are triangular, ramp, saw-tooth, pulse, TTL, rectangular, spike etc.

The oscillator shall have an amplifier with a positive feedback for generating oscillations. The basic oscillator circuit with feedback is shown below fig. 2.2.a.

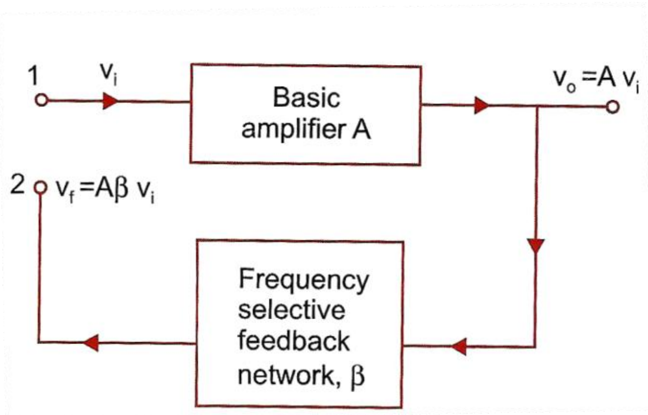


Fig.2.2.a. Basic Feedback Oscillator

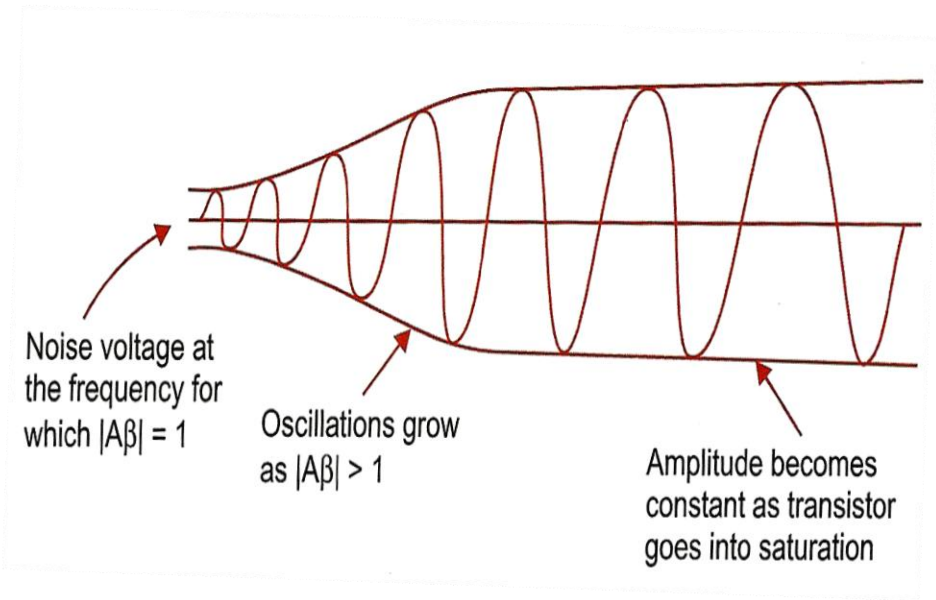


Fig.2.2.b. Feedback Oscillator Output

But for sustained (continuous and steady) oscillations Barkhausen's criteria are to be satisfied. The criteria states that

1. The total gain of the circuit should be equal to or more than one and
2. The overall phase shift in the circuit (amplifier and feedback circuit) shall be zero.

If gain of the amplifier is considered as A and feedback factor is β, then

Criterion 1: $|A\beta| \geq 1$

Modulus of the product of the amplifier gain A and feedback factor of feedback network β should be equal to or greater than zero.

Criterion 2: $\angle A\beta = 0°$ or $360°$ (0 or 2π radians)

Phase angle between the amplifier gain A and feedback factor of feedback network β or total phase shift in the circuit should be equal to or greater than zero. Criterion 1 and 2 are *Barkhausen's criteria for sustained oscillations.*

As shown in fig. 2.2.b, a noise voltage introduced by existing imbalances in the circuit is amplified by the circuit itself. The frequency of noise voltage depends on the design aspects of the circuit and when multiplication factor of total gain $|A\beta|=1$ and when $|A\beta| \geq 1$, the amplitude of the generated voltage increases till saturation is reached. Then the oscillation at the particular frequency is generated and sustained. This is done when the phase shift of the circuit is 0° or 360° (0 or 2π radians).

In the following sections two such sinusoidal oscillators are being explained. They are

(1). RC phase shift oscillator and

(2). Wien Bridge oscillator

2.2.1. RC Phase Shift Oscillators

RC phase shift oscillator generates sinusoidal output and thus categorized under sinusoidal oscillators. Here in this oscillator the amplifier used is a negative feedback inverting Operational amplifier connected to a RC feedback network.

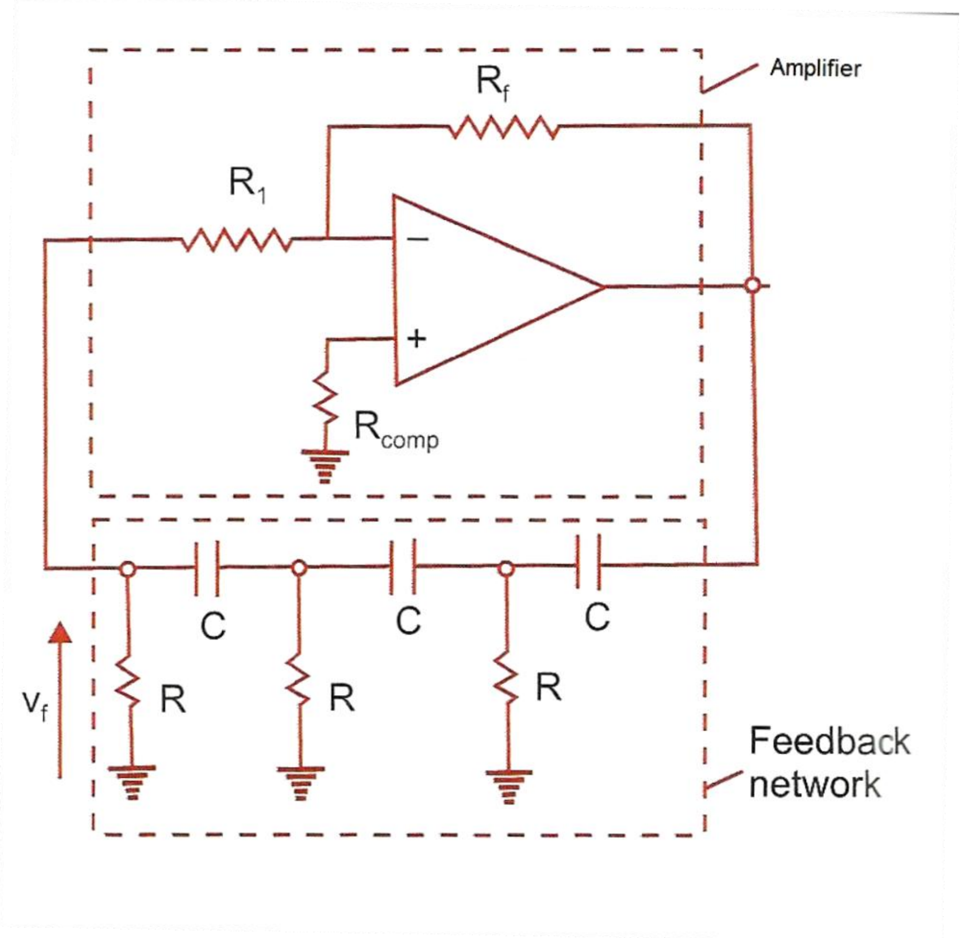


Fig.2.2.1.a. RC Phase Shift Oscillator

Construction: As described earlier the oscillator comprising of a negative feedback inverting operational amplifier whose input resistor is R1 and feedback resistor is R2 as shown in the fig. 2.2.1.a.

An RC network where one end of the resistor R is connected to the ground, the other end is connected to a capacitor C and the other end of the capacitor acts as an input terminal. The combined end of the capacitor and resistor acts as output terminal. Each RC network provides 60° ($\pi/3$ radians) phase shift between their input and output terminals. Thus three networks are connected in series, so as to provide a phase shift of 180° or π radians. The feedback RC network shifts the phase this is termed as RC phase shift oscillator. As said earlier the amplifier is an inverting amplifier, and so 180° or π radians phase shift between input and output. Hence second Barkhausen's criterion is fulfilled.

Choosing the value of amplifier voltage gain to be more (nearly 30 or so), we can fulfill first Barkhausen's criterion of having overall gain more than 1.

Working: Practically an OP AMP is not perfect and so imbalances are prevailing between their input terminals. This imbalance generates a minor sinusoidal noise voltages fed between the input terminals. This noise voltage is amplified by the amplifier and a sinusoidal output voltage V_o is generated at the output terminal.

As discussed earlier, the RC network provides 180° or 2π radians where V_o is fed into the feedback RC network and an inverse voltage of V_f shown in fig. 2.2.1.b. We can understand that V_f is 180° (or 2π radians) phase shifted V_o. This V_f is fed into the inverting terminal of the operational amplifier through an input resistor R1. This voltage is phase inverted of 180° (or 2π radians) by the amplifier and the output V_o is inverse of V_f.

Since the circuit fulfills the criteria for sustained oscillations, the circuit continuously generates sinusoidal output.

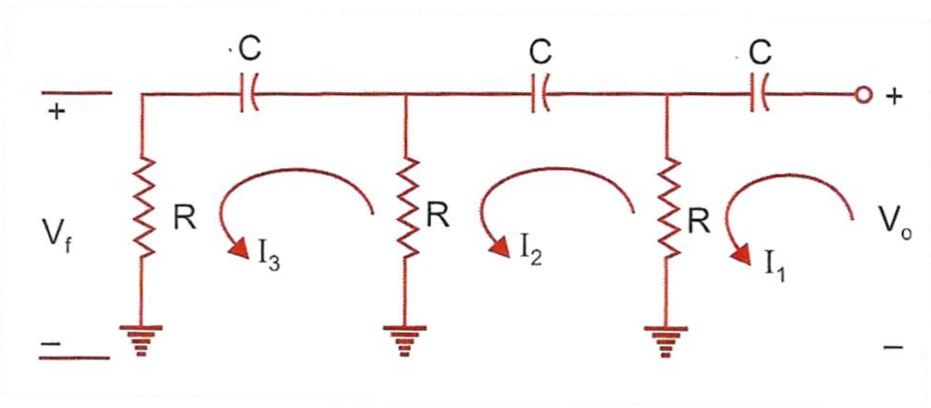


Fig.2.2.1.b. RC Phase Shift Oscillator- Feedback network

Derivation of frequency of oscillation of RC Phase shift oscillator

In the feedback network shown in Figure 3.2.1 b, the following equations are derived using KVL.

$$I_1\left[R+\frac{1}{sC}\right]+I_2\left[-R\right]+I_3\left[0\right]=V_o \quad \Rightarrow \text{Eqn } 3.2.A$$

$$I_1\left[-R\right]+I_2\left[2R+\frac{1}{sC}\right]+I_3\left[-R\right]=0 \quad \Rightarrow \text{Eqn } 3.2.B$$

$$I_1\left[0\right]+I_2\left[-R\right]+I_3\left[2R+\frac{1}{sC}\right]=0 \quad \Rightarrow \text{Eqn } 3.2.C$$

In Matrix form, the above Equation can be written as

$$\begin{bmatrix} \left[R+\frac{1}{sC}\right] & \left[-R\right] & \left[0\right] \\ \left[-R\right] & \left[2R+\frac{1}{sC}\right] & \left[-R\right] \\ \left[0\right] & \left[-R\right] & \left[2R+\frac{1}{sC}\right] \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}=\begin{bmatrix} V_o \\ 0 \\ 0 \end{bmatrix} \quad \Rightarrow \text{Eqn } 3.2.D$$

Using Cramer's Rule,

$$I_3=\frac{\Delta_3}{\Delta} \quad \Rightarrow \text{Eqn } 3.2.E$$

$$\Delta_3=\begin{bmatrix} R+\frac{1}{sC} & -R & V_o \\ -R & 2R+\frac{1}{sC} & 0 \\ 0 & -R & 0 \end{bmatrix} \quad \Rightarrow \text{Eqn } 3.2.F$$

$$\& \quad \Delta=\begin{bmatrix} R+\frac{1}{sC} & -R & 0 \\ -R & 2R+\frac{1}{sC} & -R \\ & -R & 2R+\frac{1}{sC} \end{bmatrix} \quad \Rightarrow \text{Eqn } 3.2.G$$

Solving Eqn 3.2.G in following steps

$$\Delta = \begin{bmatrix} (R+1/sC) & (-R) & 0 \\ (-R) & (2R+1/sC) & (-R) \\ 0 & (-R) & (2R+1/sC) \end{bmatrix} \Rightarrow \text{Eqn 3.2.H}$$

$$\Delta = (R+1/sC)\left[(2R+1/sC)(2R+1/sC)-(-R)(-R)\right]-(-R)\left[(-R)(2R+1/sC)\right]$$

$\Rightarrow$ Eqn 3.2.I

$$\Delta = (R+1/sC)\left[(2R+1/sC)^2-(R^2)\right]+R\left[-2R^2-R/sC\right]$$

$\Rightarrow$ Eqn. 3.2.J

$$= (R+1/sC)\left[4R^2+1/s^2C^2+4R/sC-R^2\right]-2R^3-R^2/sC$$

$$= 4R^3+\frac{R}{s^2C^2}+\frac{4R^2}{sC}-R^3+\frac{4R^2}{sC}+\frac{1}{s^3C^3}+\frac{4R}{s^2C^2}-\frac{R^2}{sC}-2R^3-\frac{R^2}{sC}$$

$$\Delta = \left[4R^3-R^3-2R^3\right]+\left[\frac{4R^2}{sC}+\frac{4R^2}{sC}-\frac{R^2}{sC}-\frac{R^2}{sC}\right]+\left[\frac{R}{s^2C^2}+\frac{4R}{s^2C^2}\right]+\frac{1}{s^3C^3}$$

$\Rightarrow$ Eqn 3.2.K

$$\boxed{\Delta = R^3+\frac{6R^2}{sC}+\frac{5R}{s^2C^2}+\frac{1}{s^3C^3}} \Rightarrow \text{Eqn 3.2.L}$$

Now value of Δ_3 to be solved. from Eqn 3.2.F

$$\Delta_3 = \begin{vmatrix} R + 1/sC & -R & V_0 \\ -R & 2R + 1/sC & 0 \\ 0 & -R & 0 \end{vmatrix} \quad \Rightarrow \text{Eqn } 3.2.M$$

$$= \left(R + 1/sC\right)[0] - (-R)[0] + V_0 [(-R)(-R)]$$

$\Rightarrow$ Eqn 3.2.N

$$= 0 - 0 + V_0 R^2$$

$$\boxed{\Delta_3 = V_0 R^2} \quad \Rightarrow \text{Eqn } 3.2.O$$

Thus using Eqns 3.2.L & 3.2.O in Eqn 3.2.E

$$I_3 = \frac{V_0 R^2}{R^3 + \frac{6R^2}{sC} + \frac{5R}{s^2C^2} + \frac{1}{s^3C^3}} \quad \Rightarrow \text{Eqn. } 3.2.P$$

The Feedback factor $\beta = \frac{V_f}{V_0}$; $V_f = I_3 R$

$$\text{Thus } \beta = \frac{I_3 R}{V_0} \quad \Rightarrow \text{Eqn } 3.2.Q$$

Substituting Eqn 3.2.P in Eqn 3.2.Q, we get

$$\beta = \frac{V_0 R^2 (R)}{(V_0)\left(R^3 + \frac{6R^2}{sC} + \frac{5R}{s^2C^2} + \frac{1}{s^3C^3}\right)} \quad \Rightarrow \text{Eqn } 3.2.R$$

$$\beta = \frac{R^3}{R^3 + \frac{6R^2}{sC} + \frac{5R}{s^2C^2} + \frac{1}{s^3C^3}} \Rightarrow \text{Eqn } 3.2.S$$

$$\beta = \frac{R^3/R^3}{\frac{R^3}{R^3} + \frac{6R^2}{R^3sC} + \frac{5R}{R^3s^2C^2} + \frac{1}{R^3s^3C^3}} \Rightarrow \text{Eqn } 3.2.T$$

$$\beta = \frac{1}{1 + \frac{6}{RsC} + \frac{5}{R^2s^2C^2} + \frac{1}{R^3s^3C^3}} \Rightarrow \text{Eqn } 3.2.U$$

Substituting $s = j\omega$ where 'ω' is angular frequency
and $s^2 = j^2\omega^2 = -\omega^2$ $[\because j^2 = -1]$
$s^3 = -j\omega^3$ in eqn 3.2.U.

$$\beta = \frac{1}{1 + \frac{6}{j\omega RC} + \frac{5}{-\omega^2R^2C^2} + \frac{1}{-j\omega^3R^3C^3}}$$

Clubbing real & imaginary parts separately

$$\beta = \frac{1}{1 - \frac{5}{\omega^2R^2C^2} + \frac{6}{j\omega RC} - \frac{1}{j\omega^3R^3C^3}} \Rightarrow \text{Eqn } 3.2.V$$

Subsitute $\alpha = \frac{1}{\omega RC}$; $\alpha^2 = \frac{1}{\omega^2R^2C^2}$ & $\alpha^3 = \frac{1}{\omega^3R^3C^3}$

Then Eqn 3.2.V becomes

$$\beta = \frac{1}{\underbrace{\left[1 - 5\alpha^2\right]}_{\text{Real}} + \frac{1}{j}\underbrace{\left[6\alpha - \alpha^3\right]}_{\text{Imaginary}}} \Rightarrow \text{Eqn } 3.2.W$$

Since $A\beta$ is a constant, β cannot have imaginary content. Thus imaginary part is zero

$$6\alpha - \alpha^3 = 0$$

$$\alpha^3 = 6\alpha$$

$$\alpha^2 = 6$$

Value of $\boxed{\alpha = \sqrt{6}}$ $\Rightarrow$ Eqn 3.2.X

Thus $\alpha = \sqrt{6} = \frac{1}{\omega RC}$

$$\omega = \frac{1}{\sqrt{6}RC}$$

$\omega = 2\pi f$ where f is frequency in Hertz.

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

Hence Frequency of Oscillation of RC Phase shift oscillator $\boxed{f = \frac{1}{2\pi RC\sqrt{6}}}$

Pblm.2.2.1-Solved Problem:

The capacitor value of an RC phase shift oscillator using OP AMP is 0.01µF and the desired frequency of oscillation is 25 KHz. The voltage gain of the amplifier should be 30. Thus calculate the value of R of RC feedback network, input resistor R1 and feedback resistor R2 connected to the amplifier.

Solution:

Value of R in RC feedback network:

Given C=0.01 µF, and Frequency f= 25 KHz.

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

Therefore

$$R = \frac{1}{2\pi fC\sqrt{6}}$$

$$R = \frac{1}{2\pi * 25 * 10^3 * 0.01 * 10^{-6} * \sqrt{6}}$$

$$R = 260\ K\Omega$$

Thus Resistor R value in RC network is 260 KΩ.

Value of R1 in amplifier circuit:

Given A=30. R1 or R2 are not given and thus we can assume any one resistor value. If R1 is assumed to be 1KΩ then R2 can be estimated. Since it is an inverting amplifier

Its gain is

$$A = \left|\frac{-R2}{R1}\right|$$

Therefore

$$30 = \frac{R2}{1K\Omega}$$

$$R2 = 30\ K\Omega$$

Thus Resistor R2 (acts as a feedback resistor) value in amplifier is 30 KΩ.

Possible questions:

What is the phase shift introduced by the three RC feedback network and how?

Explain briefly about construction and working of RC Phase shift oscillator using OP AMP with neat sketches.

Explain briefly about how RC Phase shift oscillator using OP AMP satisfies Barkhausen's criteria.

2.2.2. Wien's Bridge Oscillators

Unlike RC phase shift oscillator, Wien bridge oscillator never uses phase-shift concept. It uses balancing concept of lead-lag network.

Construction: Here this oscillator is connected in a bridge fashion. The inverting terminal is connected to a junction where resistors R_3 and R_F are connected. The other end of R_3 is grounded and R_F is connected to output terminal of the amplifier. This forms a reference voltage across R_3 being fed into inverting terminal as shown in the fig. 2.2.2.a & 2.2.2.b

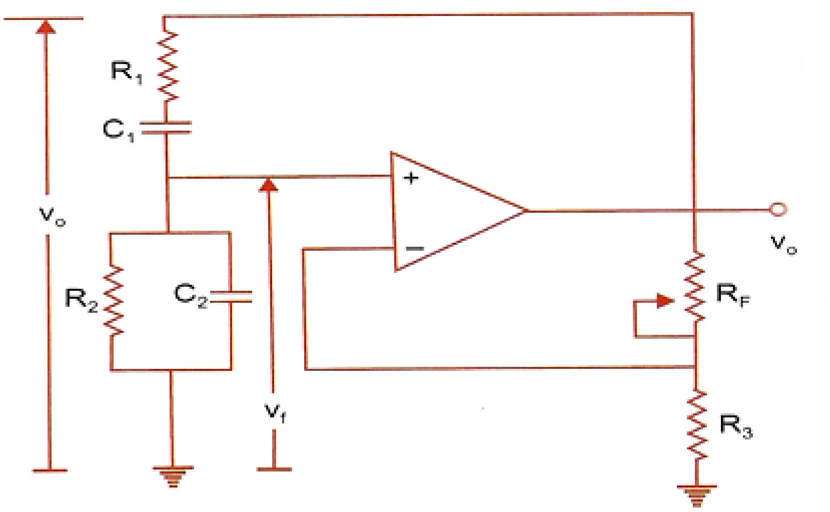


Fig.2.2.2.a. Wien's Bridge Oscillator

The non-inverting connected in between two reactance offering components Z_1 and Z_2 as shown in the fig. 2.2.2.b. Z_1 comprises of serially connected resistor R_1 and capacitor C_1 whereas Z_2 comprises of parallel connected resistor R_2 and capacitor C_2. This combination of Z_1 and Z_2 is termed as *lead-lag circuit*.

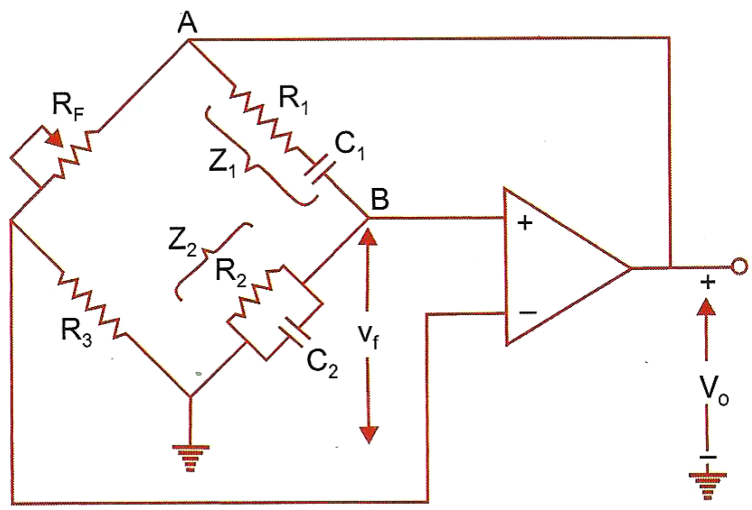


Fig.2.2.2.b. Wien's Bridge Oscillator-Reconstructed

Working: Here the reactive circuits Z_1 and Z_2 connected to non-inverting terminal at B as shown in the fig. 3.3.2.b. A noise voltage is generated between the imbalanced input terminals is amplified by the amplifier and fed in the bridge circuit.

For particular low-frequencies, the capacitors act as open circuit and thus the output voltage of lead-lag circuit shall be zero and for high frequencies the capacitors cat as short circuit and thus voltage shall be zero. Only for a particular frequency called *resonant frequency*, resistance value equals to capacitive reactance value. Thus maximum current is available at this frequency only. So the output appears only for resonant frequency.

The other resistor values of R_3 and R_F of bridge are adjusted to enhance the output to a maximum level. Thus the oscillation is generated.

The amplifier is a non-inverting amplifier circuit and so no phase shift is introduced. Phase shift is 0° (or 2π) for the whole circuit. And the overall gain shall be also more than 1. Thus the Barkhausen's criteria for sustained oscillations are satisfied.

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$ then $R = X_C$ at resonant frequency where X_C is capacitive reactance of C.

Thus

$$R = X_C = \frac{1}{2\pi f C}$$

The frequency of oscillation

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

Possible question:

Explain briefly about construction and working of Wien bridge oscillator using OP AMP with neat sketches.

2.3 OP-AMP MULTIVIBRATORS

Multivibrators are square wave oscillators that produce pulse waveforms with various ON time and OFF time. As shown in fig. 2.3.a, P1, P2 and P3 are ON time of the pulse whose total time period is 10 ms with T_{ON} and T_{OFF} are 3.5 ms and 6.5 ms respectively. T_{ON} and T_{OFF} are two states of the pulse. The place where T_{ON} transits to T_{OFF} or T_{OFF} to T_{ON} is termed as *state transition*.

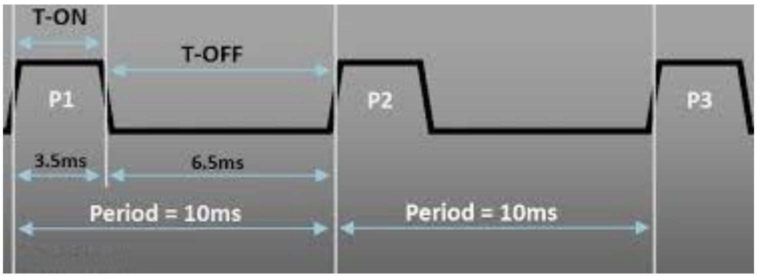


Fig.2.3.a. Pulse waveform - model

The state transition may have slope (with a small time for transition) or infinite slope (No time for transition-being abrupt).

There are three types of multivibrators available according to their state transition. They are (a.) astable, (b.) monostable, and (c). bistable multivibrators.

Astable multivibrator is one that generates pulses those transits from one state to another without any external trigger. It is done by its free-will controlled by the design aspects. Thus this is called *free-running* multivibrator. So the states are not stable for a long time, the states can be termed as Quasi-stable states. Hence this multivibrator generates pulses of no stable states, it is termed as astable multivibrator.

Monostable multivibrator is one that generates pulses those transits from one state to another with the help of *one* external trigger. The multivibrator remains in one state (stable state) and when an external pulse is applied then it transits state from present Stable state to a quasi-stable state. It remains at quasi-stable state for a time period of T as it is designed and then returns to a stable state without any external trigger. Since it changes state from stable to quasi-stable using one external trigger, it is termed as one-shot multivibrator or monostable multivibrator.

Bistable multivibrator is one that generates pulses those transits from one state to another with the help of two external trigger. The multivibrator remains in one state (stable state) and when an external pulse is applied then it transits state from present Stable state to a next stable state. It remains at second stable state until another external trigger is applied. Thus this multivibrator has stable states only and the transitions happen only when triggers are applied, it is termed as bistable multivibrators.

Other related terminology: Duty cycle means

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} \%$$

If T_{ON} is 5 ms and T_{OFF} is 10 ms, then Duty cycle D=5/15 ms, D=33%.
D=50%, then $T_{ON} = T_{OFF}$

Possible questions:
What is a Multivibrator?
Define the terminology of astable, monostable and bistable multivibrators.

2.3.1. Astable Multivibrators

These multivibrators are termed as *"Free Running"* multivibrators, and they have only quasi stable states as seen earlier in introduction.

The circuit diagram of astable multivibrator using Operational amplifier is shown below fig. 2.3.1.a.

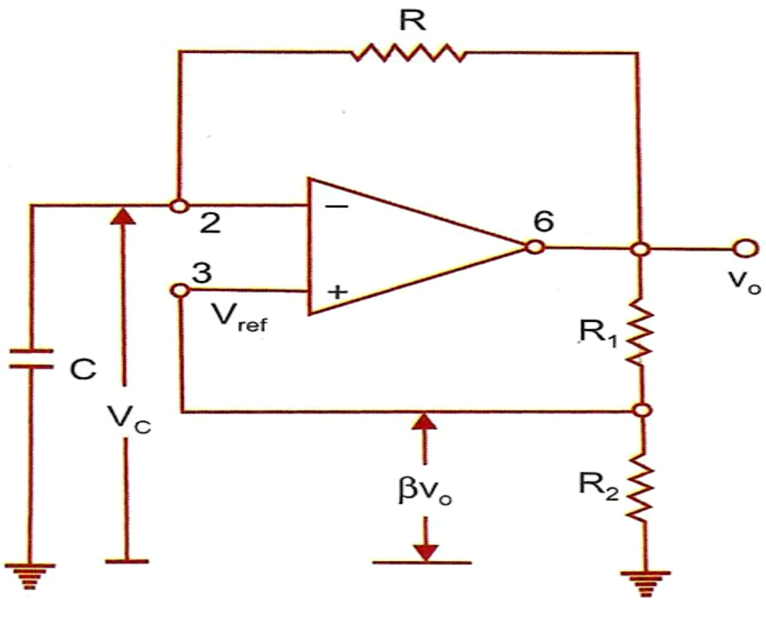


Fig.2.3.1.a. Astable Multivibrator – Circuit Diagram

Construction:

The circuit as simple and resembles like OP AMP Schmitt trigger circuit. One end of a capacitor C and a resistor R are connected to the inverting terminal. The other end of the resistor is connected to the output terminal and that of capacitor is connected to ground terminal. This capacitor C and feedback resistor R decide the period for oscillation of the multivibrator. A resistor R1 is connected between the output terminal and non-inverting terminal and another resistor R2 is connected between non-inverting terminal and ground terminals. If the output voltage is considered as V_o, then the voltage tapped between R2 shall be a reference voltage applied to the non-inverting terminal with amplitude of βV_o where β is feedback factor for comparison.

Working:

Considering fig. 2.3.1.a and 2.3.1.b, the working part of this generator can be explained.

At Time 0: At time 0, assume the output transits from $-V_{sat}$ to $+V_{sat}$. Since the output is $+V_{sat}$ at time 0, reference voltage $+\beta V_o$ and capacitor voltage is $-\beta V_o$.

From Time 0 to Time T1: Since reference is at $+\beta V_o$, the inverting terminal is also at $+\beta V_o$ due to virtual ground. Now the capacitor tries to charge till the output voltage $+V_o$. It reaches $+\beta V_o$ and tries to charge more, then the inverting terminal go beyond reference voltage $+\beta V_o$ after time constant RC.

At Time T1: At time T1, since the inverting terminal goes little above than reference voltage $+\beta V_o$, the output transits from $+V_{sat}$ to $-V_{sat}$. Now capacitor voltage remains at $+\beta V_o$. The reference voltage at non-inverting terminal is at $-\beta V_o$. The time T1 is decided by RC (time constant) factor.

After Time T1: Since reference is at $-\beta V_o$, the inverting terminal is also at $-\beta V_o$ due to virtual ground. Now the capacitor tries to charge till the output voltage $-V_o$. It tries to reach $-\beta V_o$ and tries to charge more, then the inverting terminal go beyond reference voltage $-\beta V_o$ after time RC (time constant). Now again whatever happened at time 0 happens again. These 3 steps repeat periodically till power is available for the circuit.

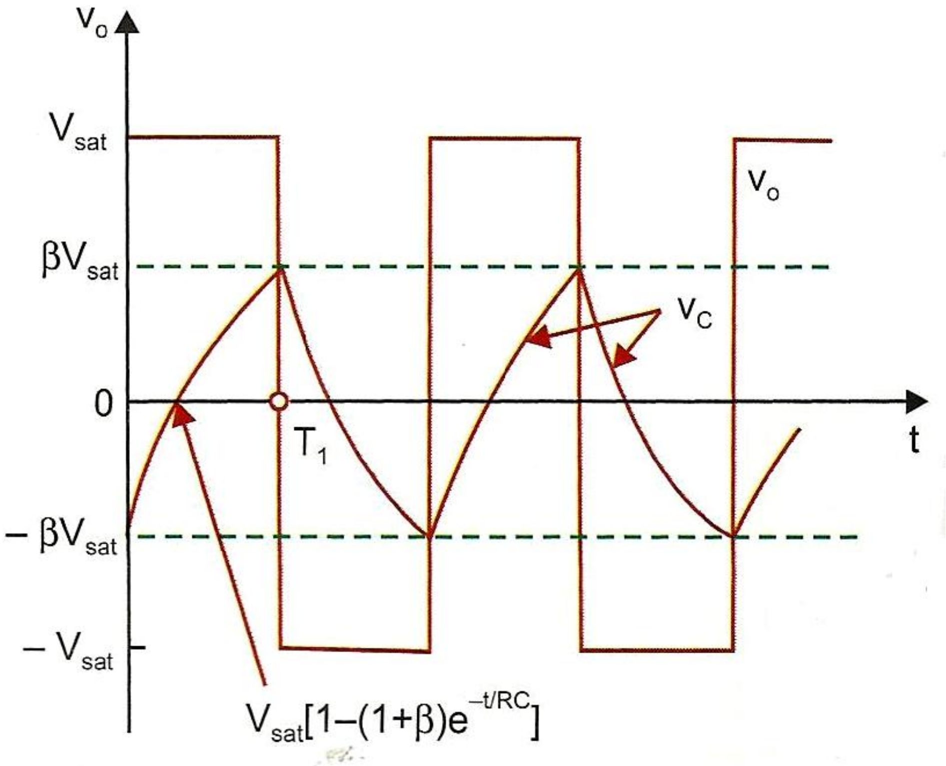


Fig.2.3.1.b. Astable Multivibrator – Output Waveforms

DERIVATION OF FREQUENCY OF OSCILLATION FOR OP-AMP ASTABLE MULTIVIBRATOR

Analysis of capacitor voltage V_C(across capacitor C)

Generally

$$V_C = V_{final} + (V_{initial} - V_{final})e^{-t/RC}$$

Where V_C is capacitor voltage, $V_{initial}$ and V_{final} are capacitors' initial and final charging voltages respectively, t is the time function, RC is time constant where R and C are value of Resistor and capacitor attached to inverting terminal of the op-amp.

In this circuit

$$.V_{initial} = -\beta V_{sat}$$

$$.V_{final} = V_{sat}$$

but capacitor charges upto $+\beta V_{sat}$ only

Now substituting these values in equation above

$$V_C = V_{sat} + (-\beta V_{sat} - V_{sat})e^{-t/RC}$$

$$V_C = V_{sat} - V_{sat}(1+\beta)e^{-t/RC}$$

At time T_1, V_C,is $+\beta V_{sat}$ (in waveform fig.2.3.1.b), the above equation becomes

$$V_C = \beta V_{sat} = V_{sat} - V_{sat}(1+\beta)e^{-T_1/RC}$$

$$V_{sat}(1+\beta)e^{-T_1/RC} = V_{sat} - \beta V_{sat}$$

$$V_{sat}(1+\beta)e^{-T_1/RC} = V_{sat}(1-\beta)$$

$$e^{-T_1/RC} = \frac{V_{sat}(1-\beta)}{V_{sat}(1+\beta)}$$

$$\frac{1}{e^{T_1/RC}} = \frac{(1-\beta)}{(1+\beta)}$$

Inverting both sides we get,

$$e^{T_1/RC} = \frac{(1+\beta)}{(1-\beta)}$$

Taking Natural logarithm on both sides,

$$T_1/RC = ln\frac{(1+\beta)}{(1-\beta)}$$

$$T_1 = RC\, ln\frac{(1+\beta)}{(1-\beta)}$$

But as shown in the figure, T_1 is only ON time and T is the total cycle time which is T_1+T_2 where T_2 is considered $=T_1$.

Then $T=2T_1$,

$$T = 2RC\, ln\frac{(1+\beta)}{(1-\beta)}$$

Since $\beta = \frac{R_2}{R_1+R_2}$ (feedback Factor), R_1 and R_2 decides value of β,

Case 1:

If $R_1=R_2$, then $\beta = \frac{1}{1+1} = 0.5$. Then

$$T = 2RC\ ln\frac{(1.5)}{(0.5)}$$

$$T = 2RC\ \ln(3)$$

$$T = 2RC\ (1.0986)$$

$$T = 2.1972\ RC$$

Case 2:

If $R_1=1.16\ R_2$, then $\beta = \frac{1}{1+1.16} = 0.462$ Then

$$T = 2RC\ \ln(2.718)$$

as $\ln(2.718) = 1$

$$T = 2RC\ (1)$$

$$T = 2RC$$

Thus when $R_1=1.16\ R_2$,

The frequency of oscillation of Astable multivibrator is

$$f = 1/T = 1/2RC$$

Possible question:

Explain construction and working of Astable Multivibrator using OP AMP using neat sketches.

2.3.2. Monostable Multivibrators

These multivibrators are termed as *"one-shot multivibrators"* and they have only one stable state and other is quasi-stable state induced by single external trigger as seen earlier in introduction.

The circuit diagram of monostable multivibrator using Operational amplifier is shown below fig. 2.3.2.a.

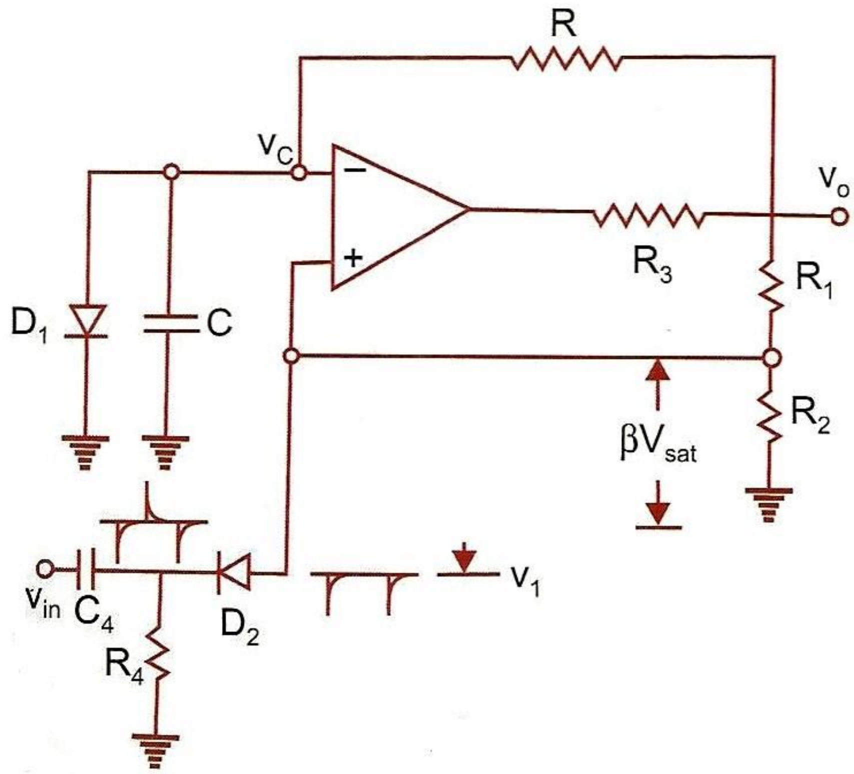


Fig.2.3.2.a. Monostable Multivibrator Using OP AMP

Construction:

The circuit as simple and resembles like OP AMP Schmitt trigger circuit. One end of a capacitor C and a resistor R are connected to the inverting terminal. The other end of the resistor is connected to the output terminal and that of capacitor is connected to ground terminal. A diode D1 is connected parallel to the capacitor C. This capacitor C and feedback resistor R decide the period for T of the multivibrator. A resistor R1 is connected between the output terminal and non-inverting terminal and another resistor R2 is connected between non-inverting terminal and ground terminals. If the output voltage is considered as V_o, then the voltage tapped between R2 shall be a reference voltage applied to the non-inverting terminal with amplitude of βV_o where β is feedback factor for comparison.

A pulse trigger circuit consisting of diode D2 and a differentiator circuit connected to pulse generator of negative pulse width T_p. The anode of the diode D2 is connected to non-inverting terminal

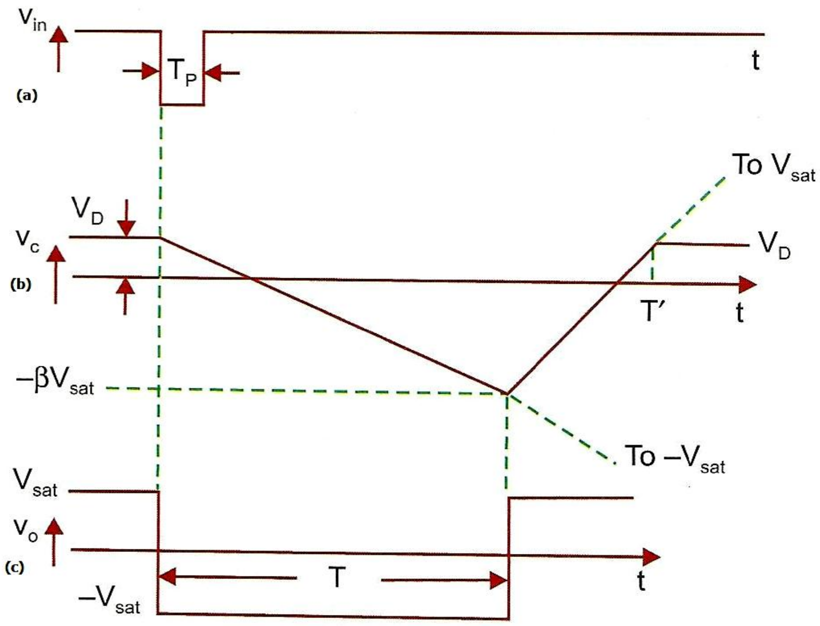


Fig.2.3.2.b. Monostable Multivibrator - Waveforms

Working:

Considering fig.'s 2.3.2.a and 2.3.2.b, the working part of this generator can be explained. In fig. 2.3.2.b has three waveforms. Waveform *a* shows the pulse trigger waveform whose trigger pulse width is T_P, waveform *b* shows voltage output V_C across capacitor C and waveform *c* shows the monostable output V_o of quasi-stable state of time T.

Before pulse trigger: At time before pulse trigger, assume the output is at $+V_{sat}$. Since the output is at $+V_{sat}$, then reference voltage is at $+\beta V_o$ and so capacitor voltage V_C tries to charge towards $+V_{sat}$. Due to this the diode D1 gets forward biased when inverting terminal is positive, and the diode D1 starts conducting beyond 0.7V (Approximate cut-in voltage of Silicon diode). Thus the diode D1 conducts and provides a short path beyond 0.7V, and hence the capacitor C which is parallel can charge upto 0.7V only. So now the capacitor voltage V_C is 0.7V.This voltage is shown as V_D in the fig. 2.3.2.b waveform (*b*).

At time of pulse trigger: As shown in fig. 2.3.2.b waveform (*a & b*), a negative pulse trigger is applied at non-inverting terminal and its amplitude being $-V_{in}$. Hence at the non-inverting terminal, pulse voltage $-V_{in}$ and reference voltage $+\beta V_{sat}$ exists. The total voltage is $(+\beta V_{sat} - V_{in})$. The amplitude of this voltage is less than 0.7V due to existence of diode D2 which is forward biased

(ON) due to –ive trigger pulse (Cathode of the diode D2 is negative due to $-V_{in}$ and anode is positive due to $+\beta V_{sat}$).

Now non-inverting terminal acts as reference terminal of an inverting comparator. At this point inverting terminal is at 0.7V and non-inverting reference voltage is below 0.7V. Hence inverting terminal is more than reference voltage at non-inverting terminal and the output transits from $+V_{sat}$ to $-V_{sat}$ as shown in fig. 2.3.2.b waveform (*c*). That is output transited from stable high state to low state.

The capacitor voltage V_C is at 0.7V and output is at $-V_{sat}$. Hence the capacitor C starts charging towards $-V_{sat}$ through the resistor R. The non-inverting terminal reference voltage is less than 0.7V.

At Time AFTER pulse trigger: When pulse trigger ends after time T_P, it becomes positive. So the cathode of diode D2 is at positive voltage and anode is at $-\beta V_{sat}$. Thus the diode D2 is in reverse bias condition (OFF). Due to this the non-inverting voltage is affected only by reference voltage across resistor R2 which is $-\beta V_{sat}$.

Now reference voltage is at $-\beta V_{sat}$ and the charging capacitor is charging towards $-V_{sat}$. but when capacitor voltage V_C reaches just above $-\beta V_{sat}$, output transits from $-V_{sat}$ to $+V_{sat}$ (Inverting terminal voltage V_C is more than reference voltage at non-inverting terminal). This transition happens at time T from start of pulse trigger where T is decided by RC time constant. That is capacitor C took time period of T for charging from V_D to $-\beta V_{sat}$ which is through resistor R. The output stays at a quasi-stable state for a time period of T.

After Time T: Now output voltage V_o is at $+V_{sat}$ and reference voltage at non-inverting terminal is at $+\beta V_{sat}$. The capacitor starts charging from $-\beta V_{sat}$ to $+V_{sat}$. But when the capacitor voltage V_C increases more than $V_{D,}$ diode D1 is forward biased and starts conducting. Hence the capacitor voltage V_C cannot charge beyond V_D. The waveform is shown in fig. 2.3.2.b waveform (*a*).

As seen initially, now the amplitude at inverting terminal is V_D due to charge of capacitor, non-inverting terminal voltage is at $+\beta V_{sat}$. The output is a negative pulse voltage whose time period is T. This negative pulse was generated due to an external negative trigger (one-shot trigger). The output transit from a stable high state to a low quasi-stable state time T and then to a stable high state. This is a monostable waveform because it has one stable state and a quasi-stable state.

In next section, discussion about derivation of time period T is done.

DERIVATION OF FREQUENCY OF OSCILLATION FOR OP-AMP MONOSTABLE MULTIVIBRATOR

Analysis of capacitor voltage V_C(across capacitor C)

Generally

$$V_C = V_{final} + (V_{initial} - V_{final})e^{-t/RC}$$

Where V_C is capacitor voltage, $V_{initial}$ and V_{final} are capacitors' initial and final charging voltages respectively, t is the time function, RC is time constant where R and C are value of Resistor and capacitor attached to inverting terminal of the op-amp.

In this circuit,

$$V_{initial} = V_D$$

$$V_{final} = -V_{sat}$$

Where (V_D= Diode Forward voltage)

Now substituting these values in equation above

$$V_C = V_{sat} + (V_D - (-V_{sat}))e^{-t/RC}$$

$$V_C = -V_{sat} + (V_D + V_{sat})e^{-t/RC}$$

At time T_1, V_C,is $-\beta V_{sat}$ (in waveform fig.2.3.2.b), the above equation becomes

$$V_C = -\beta V_{sat} = -V_{sat} + (V_D + V_{sat})e^{-T/RC}$$

$$(V_D + V_{sat})e^{-T/RC} = V_{sat} - \beta V_{sat}$$

Dividing by V_{sat},

$$(\frac{V_D}{V_{sat}} + 1)e^{-T/RC} = 1 - \beta$$

$$e^{-T/RC} = \frac{1-\beta}{(\frac{V_D}{V_{sat}} + 1)}$$

$$\frac{1}{e^{T_1/RC}} = \frac{1-\beta}{(\frac{V_D}{V_{sat}} + 1)}$$

Inverting both sides we get,

$$e^{T_1/RC} = \frac{(\frac{V_D}{V_{sat}} + 1)}{1-\beta}$$

Taking Natural logarithm on both sides,

$$T_1/RC = ln\frac{(\frac{V_D}{V_{sat}} + 1)}{1-\beta}$$

$$T_1 = RC\, ln\frac{(\frac{V_D}{V_{sat}} + 1)}{1-\beta}$$

But as shown in the figure, T_1 is time period of Monostable multivibrator, it is considered as T

Then $T=T_1$,

$$T = 2RC\, ln \frac{(\frac{V_D}{V_{sat}} + 1)}{1-\beta}$$

If $V_{sat}>>V_D$ then V_D / V_{sat} becomes negligible and $R_1=R_2$, then $\beta=0.5$,

$$T = 2RC\, ln \frac{(0+1)}{1-0.5}$$

$$T = 2RC \ln(2)$$

$$T = 0.69RC$$

The frequency of oscillation of monostable multivibrator is (if $R_1=R_2$)

$$f = 1/T = 1/0.69RC$$

$$f = 1/T = 1.45/RC$$

Possible question:

Explain the construction and working of monostable multivibrator using OP AMP with neat sketches.

2.4 OP-AMP RECTIFIERS

2.4.1 PRECISION RECTIFIERS

Rectifiers convert bipolar AC signals into unipolar DC signals. The circuit mainly uses diodes that block signals when reverse biased and allow signals when forward biased. But when forward biased diode can only allow signals above 0.7V (cut-in voltage of Silicon diode). So the rectifier cannot precisely rectify ac signals of peak to peak voltages below 0.7V. For eradicating this disadvantage of not rectifying signals below 0.7V we use operational amplifiers for rectification.

OP AMP inverting amplifier circuits are added with diodes to function as precision rectifiers to rectify voltages below 0.7V (cut-in voltages).

2.4.1. Precision Half-wave Rectifiers

As discussed this precision rectifier is used for rectifying ac signals below cut-in voltages.

Circuit construction: An inverting amplifier with input resistor R1 and feedback resistor R2 is altered by adding two diodes D1 and D2 in series as shown in the fig. 2.4.1.a. D1 is connected between output terminal of OP AMP and resistor R2 as shown and diode D2 is connected between input inverting terminal and anode of the diode D1.

Working: An AC signal V_{in} is applied to the inverting terminal and output V_o is tapped at the cathode of diode D1 and one end of resistor R2 as shown in the following fig. The analysis of this circuit in both positive and negative cycle becomes essential.

In positive cycle: The inverting terminal becomes positive in positive input cycle and since it is an inverting amplifier and output terminal becomes negative. Thus Diode D1 becomes reverse biased and remains in OFF state but diode D2 becomes forward biased and remains ON. Since Diode D1 is OFF and diode D2 is ON and D2 provides short circuit between inverting and non-inverting terminals, so the output V_{out} is zero.

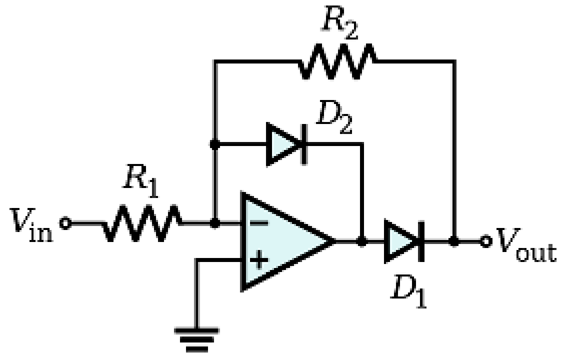


Fig. 2.4.1.a Half-wave precision rectifier

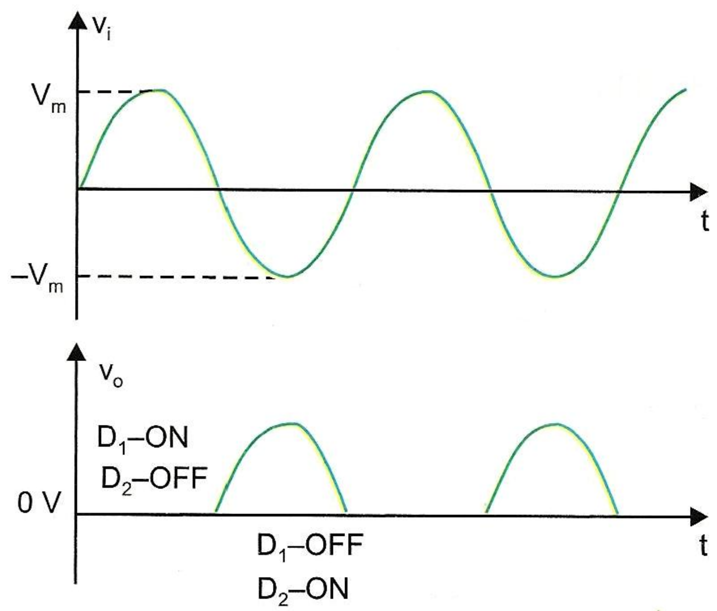


Fig. 2.4.1.b Half-wave precision rectifier-waveforms

In negative cycle: The inverting terminal becomes negative in negative input cycle and since it is an inverting amplifier and output terminal becomes positive. Thus Diode D1 becomes forward biased and remains in ON state but diode D2 becomes reverse biased and remains OFF. Since Diode D1 is ON and diode D2 is OFF and provides high resistance path between inverting and non-inverting terminals. But resistor R2 provides alternate path between input and output. Since D1 is ON, it connects V_{out} with output terminal. Now the circuit becomes normal inverting amplifier and so output V_{out} is the input multiplied by scaling factor (-R2/R1).

Thus the rectifier circuit allows one cycle (negative half cycle of the input) but blocks other cycle (positive half cycle). Since the diode doesn't directly involve in rectification and OP AMP has high gain factor, this circuit rectifies even signals less than cut-in voltage. The waveforms are shown in the fig. 2.4.1.b.

2.4.2. Precision Full-wave Rectifiers

Circuit construction: Two inverting amplifiers with input resistor R and feedback resistor R is altered by adding two diodes D1 and D2 in series as shown in the fig. 2.4.2.a. D1 is connected between output terminal of OP AMP and feedback resistor R as shown and diode D2 is connected between output terminal and other end of the resistor R connected to inverting terminal of the first OP AMP and also connected to non-inverting terminal of the second OP AMP.

Working: An AC signal V_i is applied to the inverting terminal through the resistor R and output V_o is tapped at output of second OP AMP as shown in the following fig. The analysis of this circuit in both positive and negative cycle becomes essential.

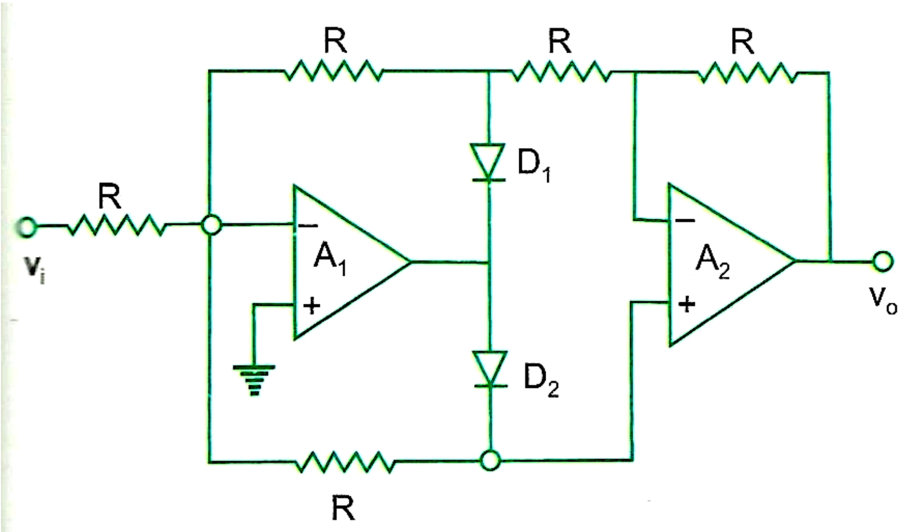


Fig. 2.4.2.a Full-wave precision rectifier

In positive cycle: The inverting terminal of first OP AMP becomes positive, in positive input cycle and diode D1 is forward biased. But diode D2 is reverse biased because output terminal becomes negative. Now D1 is ON and D2 is OFF. The circuit looks as shown in fig. 2.4.2.b. Thus output voltage V_o is double inverted signal of input voltage V_i. Since gain of both amplifiers is R/R=1, and $V_o = V_i$.

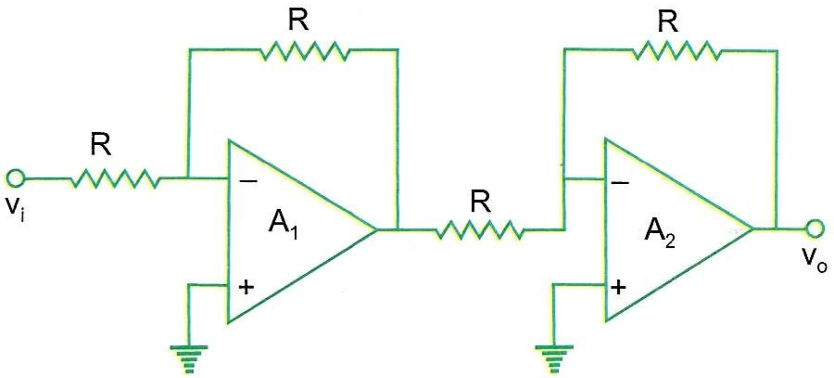


Fig. 2.4.2.b Full-wave precision rectifier-during positive half cycle

In negative cycle: The inverting terminal of the first OP AMP becomes negative in negative input cycle, the Diode D1 becomes reverse biased and remains in OFF state but diode D2 becomes forward biased and remains ON. Since Diode D1 is OFF and diode D2 is ON as shown in fig. 2.4.2.c. But resistor R provides alternate path between input and output. In second amplifier, voltage at inverting terminal is V/2R volts and non-inverting terminal is V/R. thus non-inverting terminal of second amplifier holds two times of voltage than inverting terminal. Thus output voltage V_o is ((V/R)-(V/2R)=V/2R) and is adjusted by changing the value of Feedback resistor R of second amplifier. Hence we get output for negative half-cycle too.

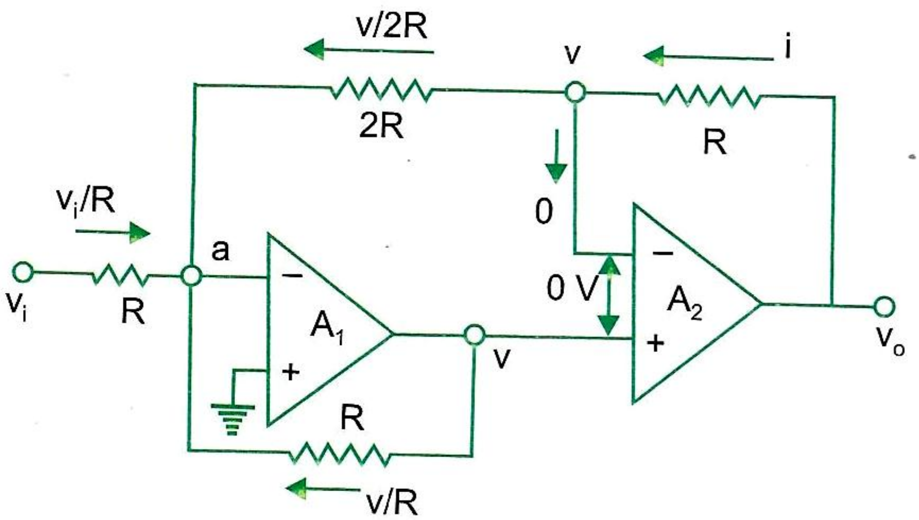


Fig. 2.4.2.c Full-wave precision rectifier-during negative half cycle

This is shown in the fig. of waveforms fig. 2.4.2.d. thus this rectifier converts bipolar AC input to unipolar DC output.

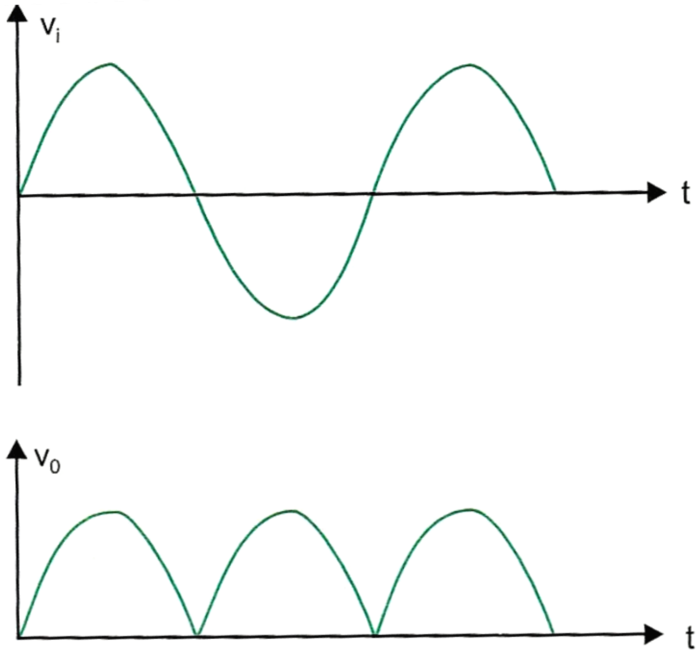


Fig. 2.4.2.d Full-wave precision rectifier waveform

Possible questions:

What is the principle behind precision rectification?

Explain the construction and working of half and full wave precision rectifiers with neat sketches.