Feedback Amplifiers and Oscillators

Topics Covered from Module 4: *Feedback Amplifiers – Principle, Properties and Advantages of Negative feedback, Types of Feedback, Voltage Series Feedback, Gain Stability with Feedback. Oscillators – Barkhausen's Criteria for Oscillation, RC Phase Shift Oscillator, Wien Bridge Oscillator. IC 555 Timer and Astable Oscillator using IC 555.*

Feedback Amplifiers – Principle

The purpose of an amplifier is to amplify the input signal without changing its characteristics except its amplitude. The amplifier that works on the principle of feedback is called *feedback amplifier*.

Feedback is a process where a fraction of the output (voltage/current) is fed back to the input. A simple block diagram of a feedback amplifier is shown in Fig. 1.

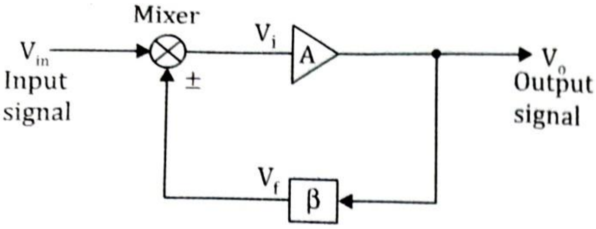


Fig. 1 Block diagram of a feedback amplifier

The input signal V_{in} is applied to a mixer network, in which it is combined with a feedback signal V_f. The difference of these signals V_i is the input to the amplifier. A portion of the amplifier output is connected to the input through a feedback network as shown in Fig. 1.

If the input signal and the feedback signal are in same phase, the signals get added up and the resultant output increases. This is called *positive feedback*. Positive feedback is also known as regenerative or direct feedback.

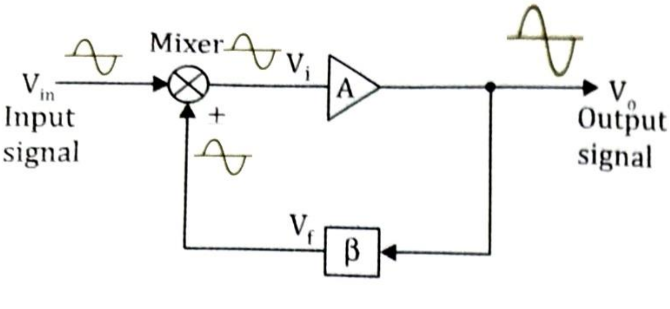


Fig. 2 Block diagram of a positive feedback amplifier

Positive feedback causes distortion and instability in amplifiers and hence it is not used for amplifiers; whereas positive feedback increases the gain and overall power of input signal and hence used in oscillator circuits. Fig. 2 shows a positive feedback amplifier.

If the input signal and the feedback signal are in opposite phase, the resultant input signal is the difference of input and feedback signals. This is called *negative feedback*. Negative feedback is also known as degenerative or inverse feedback.

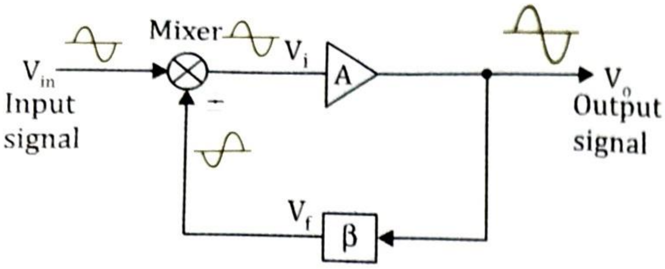


Fig. 3 Block diagram of a negative feedback amplifier

Negative feedback induces desirable modifications in circuit performance. Though negative feedback reduces the overall gain of the amplifier, it has numerous advantages and hence widely used in amplifier circuits. Fig. 3 shows a negative feedback amplifier.

Properties of Negative Feedback Amplifier

The various properties of a negative feedback amplifier are:

- **Desensitize the gain:** It brings stability to amplifier by making gain less sensitive to all kind of variations.
- **Reduce non-linear distortion:** The negative feedback makes the output proportional to the input, i.e. reduces non-linear distortion.
- **Reduce the effect of noise:** It minimizes the contribution of unwanted electric signals. This noise may be generated by circuit components or by extraneous interference.
- **Control the input and output impedances:** It increases or decreases the input and output impedances. This is done by choosing appropriate feedback topology.
- **Extend the bandwidth of the amplifier:** By incorporating negative feedback, the bandwidth can be increased.

Advantages of Negative Feedback Amplifier

In a negative feedback amplifier, the gain of the amplifier reduces. However, it is still used in almost every amplifier due to its various advantages. Some of the advantages are given below:

- Gain stability
- Significant extension of bandwidth
- Very less distortions
- Decreased output resistance
- Stable operating point
- Reduces noise and other interference in amplifier

Types of Feedback

There are four types of feedback:

- Voltage series feedback
- Voltage shunt feedback

- Current series feedback
- Current shunt feedback

Fig. 4 shows the different types of feedback amplifier circuits.

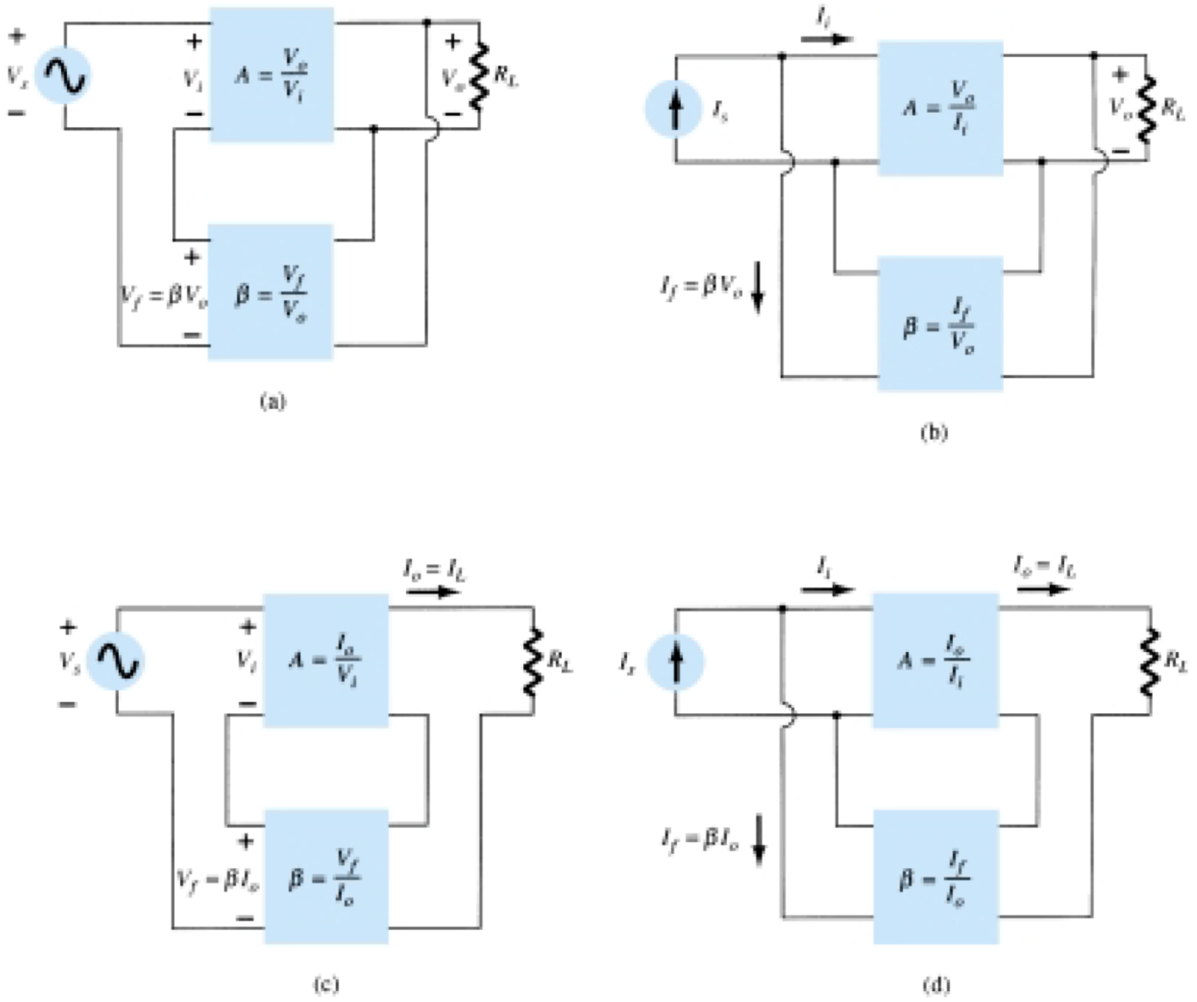


Fig. 4 Feedback amplifier types (a) Voltage series feedback (b) Voltage shunt feedback (c) Current series feedback (d) Current shunt feedback

Series feedback connections tend to increase the input resistance, while shunt feedback connections tend to decrease the input resistance. Voltage feedback tends to decrease the output impedance, while current feedback tends to increase the output impedance. Typically, higher input and lower output impedances are desired for most cascade amplifiers. Both of these are provided using the voltage series feedback connection.

Voltage Series Feedback

Consider a voltage series feedback circuit as shown in Fig. 5. Here the voltage is sampled at the output and fed back in series with the input. It is also known as series-parallel feedback.

The gain of the basic amplifier (without feedback) is

$$A = \frac{V_o}{V_i} \tag{1}$$

This gain A is also known as open loop gain.

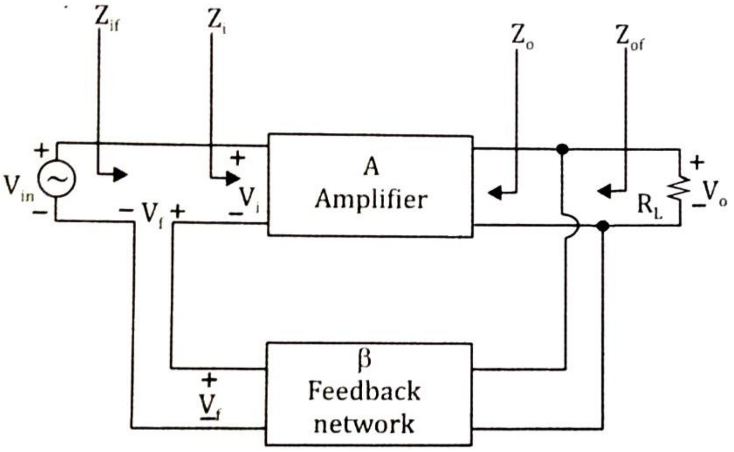


Fig. 5 Block diagram of voltage series feedback amplifier

The overall gain of the amplifier (with feedback) is

$$A_f = \frac{V_o}{V_{in}} \tag{2}$$

This gain A_f is also known as closed loop gain.

The feedback factor is $$\beta = \frac{V_f}{V_o} \tag{3}$$

From Eqn. (1), we have $$V_o = AV_i \tag{4}$$

From Eqn. (3), we have $$V_f = \beta V_o \tag{5}$$

From Fig. 5, $$V_i = V_{in} - V_f \tag{6}$$

Using Eqn. (5) in (6), $$V_i = V_{in} - \beta V_o \tag{7}$$

Using Eqn. (7) in (4), $$V_o = A(V_{in} - \beta V_o)$$

$$V_o = AV_{in} - \beta AV_o$$

$$V_o + \beta AV_o = AV_{in}$$

$$V_o(1 + \beta A) = AV_{in}$$

The overall gain (with feedback) is then given by

$$A_f = \frac{V_o}{V_{in}} = \frac{A}{1+\beta A} \tag{8}$$

Thus, the negative feedback reduces the gain by a factor $(1 + \beta A)$.

If $\beta A \gg 1$, Eqn. (8) becomes $$A_f \approx \frac{1}{\beta}$$

This means that the feedback gain is independent of amplifier gain A. Any variation in magnitude of A does not appear in A_f, which means A_f has high gain stability.

Input Impedance

Let Z_i be the input impedance without feedback. Then, the input impedance increases with feedback and is given by

$$Z_{if} = Z_i(1 + \beta A)$$

Output Impedance

Let Z_o be the output impedance without feedback. Then, the output impedance decreases with feedback and is given by

$$Z_{of} = \frac{Z_o}{1 + \beta A}$$

Gain and Bandwidth of Feedback Amplifier

The negative feedback reduces the gain of the amplifier. As the gain-bandwidth product of an amplifier is constant, the bandwidth increases with feedback.

Consider a frequency response of an amplifier with and without feedback as shown in Fig. 6.

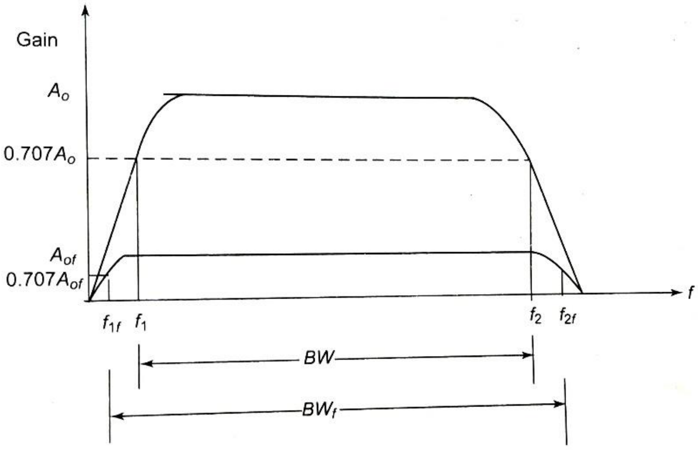


Fig. 6 Effect of negative feedback on gain and bandwidth

As $f_1 \ll f_2$ and $f_{1f} \ll f_{2f}$,

Bandwidth without feedback $BW = f_2 - f_1 \approx f_2$

and bandwidth with feedback $BW_f = f_{2f} - f_{1f} \approx f_{2f}$

A_o is the midband gain without feedback and A_{of} is the midband gain with feedback.

At high frequency, amplifier acts as low pass circuit.

Gain of the amplifier without feedback is given as

$$A = \frac{A_o}{1 + \left(j \frac{\omega}{\omega_2}\right)}$$

Gain of the amplifier with feedback is given as

$$A_f = \frac{A_{of}}{1 + \left(j \frac{\omega}{\omega_{2f}}\right)}$$

The gain-bandwidth product of an amplifier is a constant. That is,

$$A_o f_2 = A_{of} f_{2f} = constant$$

Gain Stability with Feedback

We have the overall gain of an amplifier with negative feedback,

$$A_f = \frac{A}{1+\beta A}$$

Differentiating both sides w.r.t. A,

$$\frac{dA_f}{dA} = \frac{d}{dA}\left(\frac{A}{1+\beta A}\right) = \frac{1}{(1+\beta A)^2}$$

Rearranging,

$$\frac{dA_f}{dA} = \frac{1}{(1+\beta A)}\frac{1}{(1+\beta A)}$$

$$\frac{dA_f}{dA} = \frac{1}{(1+\beta A)}\frac{A_f}{A}$$

$$\frac{dA_f}{A_f} = \frac{1}{(1+\beta A)}\left(\frac{dA}{A}\right)$$

If $\beta A \gg 1$,

$$\frac{dA_f}{A_f} = \frac{1}{\beta A}\left(\frac{dA}{A}\right)$$

This shows that a relative change (dA/A) in the basic amplifier gain is reduced by the factor βA in the relative change (dA_f/A_f) in the overall gain of the feedback amplifier, thereby increasing the gain stability.

Oscillators – Introduction

An oscillator is a circuit that produces a repetitive waveform at the output without the application of an external input signal. It receives dc energy and changes it into ac energy of derived frequency. The frequency of oscillations depends upon the constants of the device.

Classification of Oscillators

1. Based on operating principle
    a) Negative resistance effect oscillators
    b) Feedback oscillators
2. Based on type of output waveform
    a) Sinusoidal oscillators (Harmonic oscillators)
    b) Non-sinusoidal oscillators (Relaxation oscillators)
3. Based on frequency generation
    a) Audio Frequency (AF) oscillators (20 Hz to 20 kHz)
    b) Radio Frequency (RF) oscillators (20 kHz to 30 MHz)
    c) Very High Frequency (VHF) oscillators (30 MHz to 300 MHz)

   d) Ultra High Frequency (UHF) oscillators (300 MHz to 3 GHz)
   e) Microwave oscillators (300 MHz to 300 GHz)
4. Based on the circuit employed
   a) RC oscillators
   b) LC oscillators

Barkhausen's Criteria for Oscillation

Consider a basic inverting amplifier with an open-loop gain A as shown in Fig. 7. As the basic amplifier is inverting, it produces a phase shift of 180° between input and output.

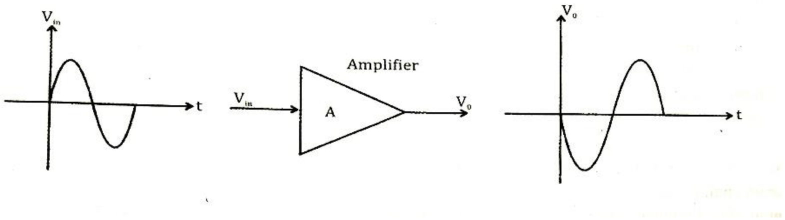


Fig. 7 Basic inverting amplifier

Now, the input V_i applied to the amplifier is to be derived from its output V_o using feedback network. But the feedback must be positive, i.e., the voltage derived from the output using feedback network must be in phase with V_i. Thus, the feedback network must introduce a phase shift of 180° while feeding back the voltage from output to input.

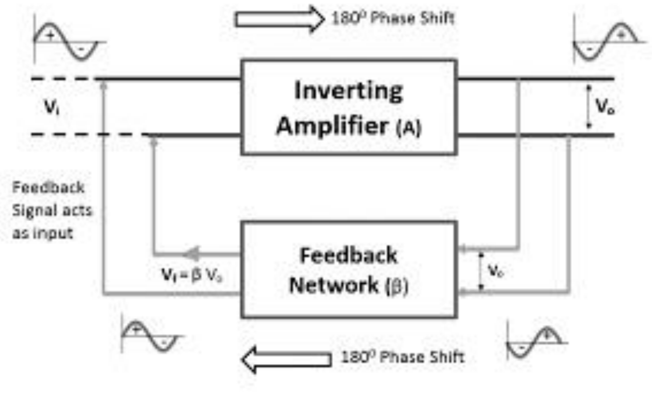


Fig. 8 Inverting amplifier with a feedback

Consider a voltage V_i applied at the input of the amplifier shown in Fig. 8.

If A is the gain, the output is given as

$$V_o = AV_i \tag{1}$$

The feedback factor β decides the feedback to be given to the input.

$$V_f = \beta V_o \tag{2}$$

Substituting Eqn. (1) in (2),

$$V_f = \beta AV_i \tag{3}$$

For the oscillator, we want the feedback should drive the amplifier and hence V_f must act as V_i. From Eqn. (3), we see that V_f is sufficient to act as V_i when $|\beta A| = 1$ and the phase of V_f is same as that of V_i, i.e., feedback network should introduce 180° phase shift in addition to the 180° phase shift introduced by the inverting amplifier. So total phase shift around the loop is 360°. These two conditions required to make the circuit work as an oscillator are called *Barkhausen's criteria for oscillation*.

It states that:

1. The magnitude of the product of the open loop gain of the amplifier A and the feedback factor β is unity, i.e., $|\beta A| = 1$.
2. The total phase shift around the loop is 0° or 360°.

In reality, no input signal is needed to start the oscillations. In practice, $|\beta A|$ is made greater than 1 to start the oscillations and then the circuit adjusts itself to get $|\beta A| = 1$, resulting in self-sustained oscillations as shown in Fig. 9.

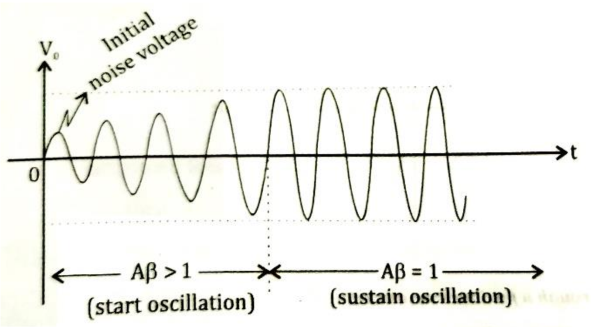
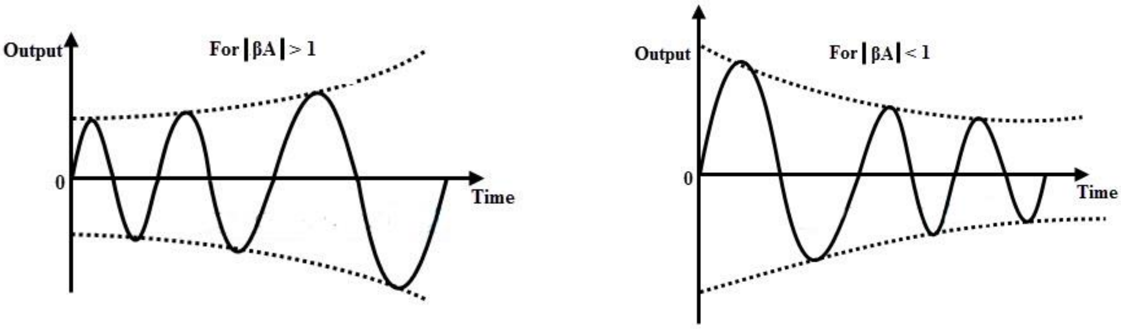
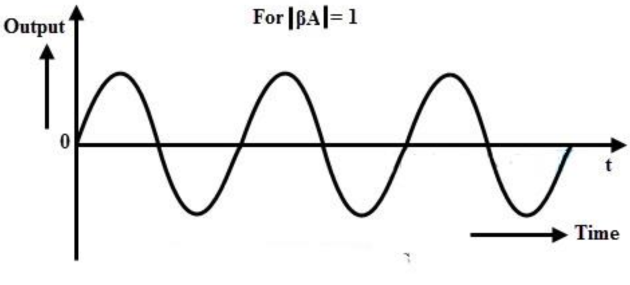


Fig. 9 Build up of oscillations



(a) Growing oscillations (b) Decaying oscillations



(c) Sustained oscillations

Fig. 10 Oscillations for different values of $|\beta A|$

As shown in Fig. 10, if $|\beta A| > 1$, the oscillations are of growing type.

If $|\beta A| < 1$, the oscillations are of decaying type, i.e., the amplitude decreases and finally oscillations stop.

If $|\beta A| = 1$, the oscillations are with constant frequency and amplitude and are called sustained oscillations.

RC Phase Shift Oscillator

The circuit of an RC phase shift oscillator is shown in Fig. 11. The circuit consists of three RC stages as shown. Each of the three RC stages in the feedback loop can provide a maximum phase shift of approximately 90°.

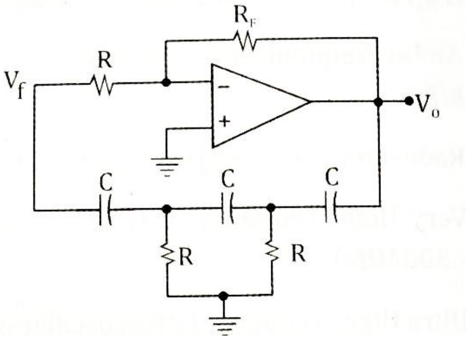


Fig. 11 RC phase shift oscillator

Oscillation occurs at the frequency for which the total shift through the three RC stages is 180° (Each stage provides 60° phase shift). The op-amp in inverting mode provides the additional phase shift of 180° to meet the requirement for oscillations of 360° (or 0°) phase shift around the loop.

The feedback network consisting of three RC stages can be rewritten as in Fig. 12.

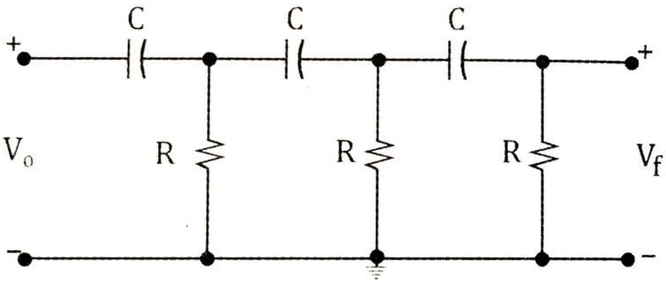


Fig. 12 Feedback network of RC phase shift oscillator

For three equal RC stages, the feedback factor (attenuation) is given by

$$\beta = \frac{V_f}{V_o} = \frac{1}{29}$$

Barkhausen’s criterion is $|\beta A| > 1$, i.e., $|A| > 29$.

That is, the voltage gain A of the amplifier must be greater than 29.

The frequency of oscillation is given by

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

The closed loop voltage gain (inverting mode) is

$$A = \frac{-R_f}{R}$$

To start the oscillations, $|\beta A| > 1$

That is, $|A| > 29 \Rightarrow |A| = \frac{R_f}{R} > 29$

Then $R_f > 29R$

For sustained oscillations, $|\beta A| = 1$

Then $R_f = 29R$

Wien Bridge Oscillator

The Wien bridge oscillator is shown in Fig. 13.

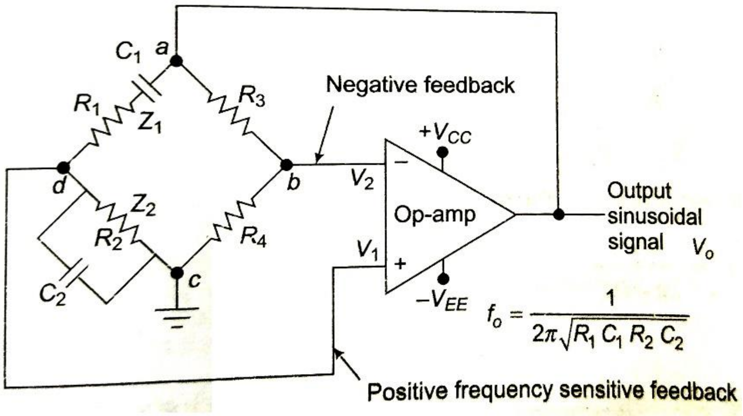


Fig. 13 Wien bridge oscillator

The feedback network comprises of a Wien bridge circuit. The op-amp is used in non-inverting mode. Oscillation occurs at the frequency for which the phase shift through the Wien bridge is 0°, because the amplifier is in non-inverting mode.

For Wien bridge network with $R_1 = R_2 = R$ and $C_1 = C_2 = C$, the feedback factor (attenuation) is given by

$$\beta = \frac{V_f}{V_o} = \frac{1}{3}$$

Barkhausen's criterion is $|\beta A| > 1$, i.e., $|A| > 3$.

That is, the voltage gain A of the amplifier must be greater than 3.

The frequency of oscillation is given by

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

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then frequency of oscillation is

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

The closed loop voltage gain (non-inverting mode) is

$$A = 1 + \frac{R_3}{R_4}$$

To start the oscillations, $|\beta A| > 1$

That is, $|A| > 3 \Rightarrow \ |A| = 1 + \frac{R_3}{R_4} > 3$

Then $$R_3 > 2R_4$$

For sustained oscillations, $|\beta A| = 1$

Then $$R_3 = 2R_4$$

IC 555 Timer

The 555 timer is a popular and versatile analog-digital integrated circuit (IC). It can be used to generate precise time delays and timing pulses whose duration and frequency are determined by an externally connected timing resistor and capacitor.

IC 555 timer is an 8-pin package as shown in Fig. 14. It requires a power supply V_{CC} which can range from +5V to +18V.

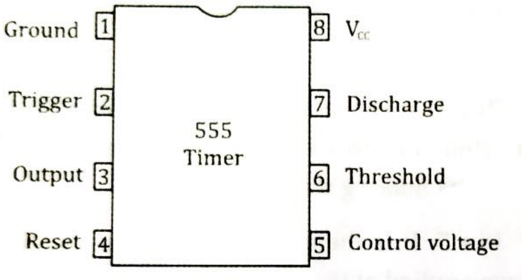


Fig. 14 Pin diagram of IC 555 timer

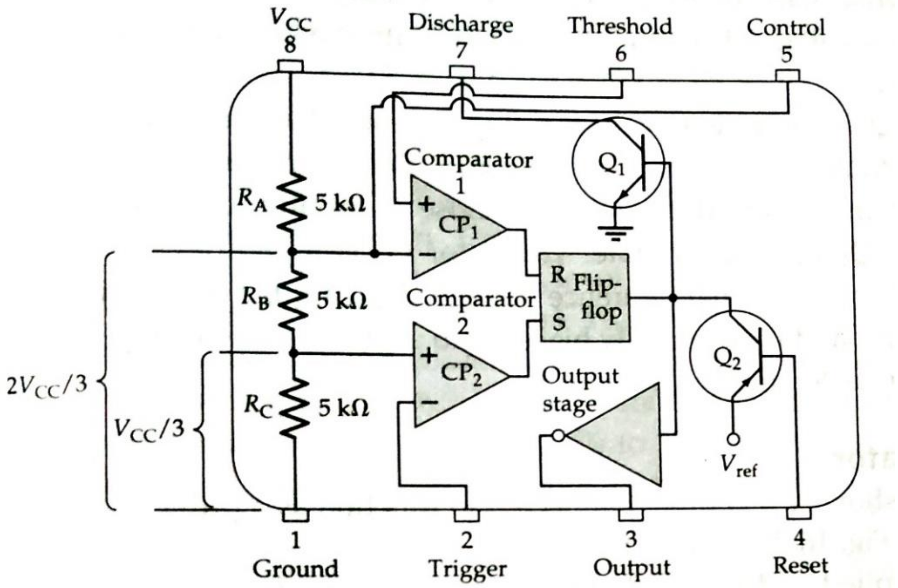


Fig. 15 Internal functional diagram of 555 timer

Fig. 15 shows the internal details of 555 timer. It consists of 2 op-amp comparators set at $\frac{2}{3}V_{CC}$ and $\frac{1}{3}V_{CC}$ using three 5 $k\Omega$ internal resistors which act as voltage divider.

Astable Oscillator using IC 555

A common application of the 555 timer is as astable multivibrator or clock circuit. Fig. 16 shows an astable oscillator circuit built using two external resistors and a capacitor.

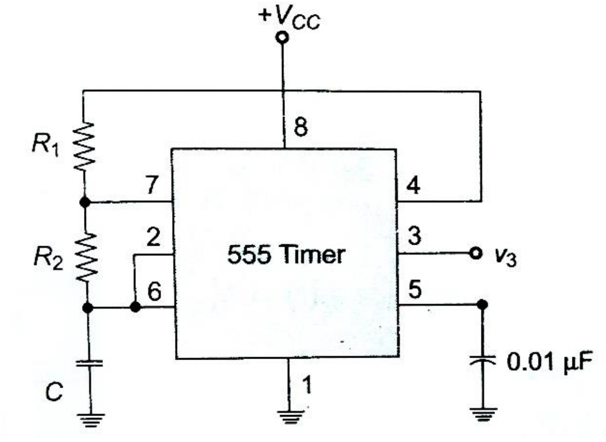


Fig. 16 Astable oscillator using 555 timer

When the power supply V_{CC} is turned ON, the external timing capacitor C charges towards V_{CC} through R_1 and R_2 with time constant $T_1 = (R_1 + R_2)C$. During this time, the output (pin 3) is HIGH ($\cong V_{CC}$), because $R = 0$ and $S = 1$ makes the flip-flop output $Q = 1$ and $\bar{Q} = 0$.

When the capacitor voltage V_C tends to increase beyond $\frac{2}{3}V_{CC}$, the comparator 1 saturates and its output becomes HIGH causing flip-flop's $R = 1$ and thus $Q = 0$ and $\bar{Q} = 1$. This makes the output LOW. This, in turn, makes the transistor Q_1 ON and capacitor C starts discharging towards ground through R_2 with time constant $T_2 = R_2C$.

When the capacitor voltage V_C tends to fall beyond $\frac{1}{3}V_{CC}$, the comparator 2 saturates and its output becomes HIGH causing flip-flop's $S = 1$ and thus $Q = 1$ and $\bar{Q} = 0$. This makes the output HIGH. This, in turn, makes the transistor Q_1 OFF and capacitor C starts charging again.

The capacitor C is thus periodically charged and discharged between $\frac{2}{3}V_{CC}$ and $\frac{1}{3}V_{CC}$ respectively.

The capacitor voltage V_C and the output voltage V_o are shown in Fig. 17.

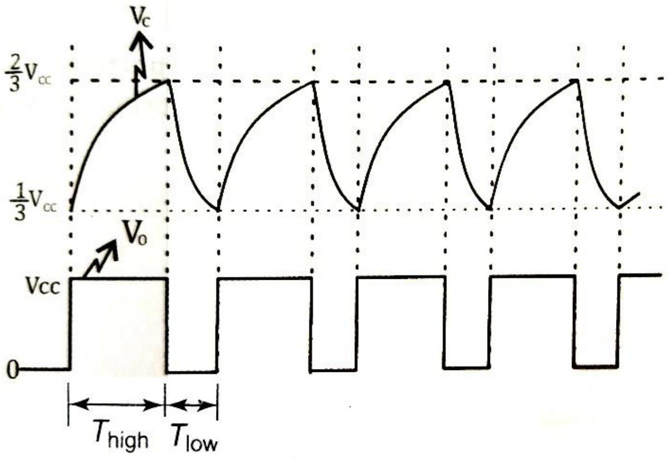


Fig. 17 Voltages V_C and V_o

The time for which output V_o is HIGH is the time during which the capacitor charges.

$$T_{high} = 0.693(R_1 + R_2)C$$

The time for which output V_o is LOW is the time during which the capacitor discharges.

$$T_{low} = 0.693R_2C$$

The period of oscillation

$$T = T_{high} + T_{low} = 0.693(R_1 + 2R_2)C$$

The oscillation frequency

$$f = \frac{1}{T} = \frac{1}{0.693(R_1 + 2R_2)C} = \frac{1.44}{(R_1 + 2R_2)C}$$

The duty cycle is given by

$$Duty\ cycle = \frac{T_{high}}{T_{high} + T_{low}} = \frac{0.693(R_1 + R_2)C}{0.693(R_1 + 2R_2)C}$$

$$\%\ Duty\ cycle = \frac{R_1 + R_2}{R_1 + 2R_2} \times 100\%$$

Questions

1. What is feedback amplifier? What are the properties of negative feedback amplifier? ***(Jul '19 – 6M)***
2. What is a feedback amplifier? Briefly explain different types of feedback amplifiers. ***(MQP '18 – 6M)***
3. Define feedback amplifier. With necessary diagram and equation explain the different types of feedback. ***(MQP '18 – 12M)***
4. List the advantages of negative feedback in an amplifier. Explain the voltage series feedback amplifier. Show that the gain bandwidth product for a feedback amplifier is constant. ***(MQP '18 – 10M)***
5. Mention types of feedback amplifier. With block diagram, explain voltage series feedback amplifier. ***(Sep '20 – 6M)***
6. Draw and explain the operation of a voltage series feedback amplifier circuit and derive an expression for its voltage gain A_V with feedback. ***(Feb '21 – 6M, Jan '20 – 4M, Jul '19 – 6M, Jan '19 – 4M, MQP '18 – 6M)***
7. With necessary equations, explain how gain is stabilized by using feedback.
8. Explain the Barkhausens' criteria for oscillations. ***(Feb '21 – 6M, MQP '18 – 6M)***
9. What is an oscillator? Write a note on classification of oscillators.
10. What is phase shift oscillator? Explain with circuit, RC phase shift oscillator. ***(Sep '20 – 8M)***
11. Explain RC phase shift oscillator with circuit diagram and necessary equations. ***(Feb '21 – 8M, Jan '20 – 8M, Jan '19 – 8M, MQP '18 – 6M)***

12. With a neat circuit diagram, explain the working of Wien bridge oscillator. ***(Jan '20 – 8M, Jul '19 – 8M)***
13. Define an oscillator. Derive the equation for Wien bridge oscillator. ***(Feb '21 – 8M, MQP '18 – 8M)***
14. Write a note on IC 555 timer.
15. Explain the operation of IC-555 timer as an astable oscillator with neat circuit diagram and necessary equations. ***(Feb '21 – 8M, Jan '20 – 8M, Jul '19 – 8M, Jan '19 – 8M, MQP '18 – 8M)***
16. Explain with circuit, astable multivibrator using IC 555. ***(Sep '20 – 6M)***
17. A negative feedback amplifier has gain $A = 1000$ and bandwidth of 200 kHz. Calculate gain and bandwidth with feedback if feedback factor $\beta = 20\%$. ***(Sep '20 – 6M)***
18. An amplifier has a high frequency response described by $A = \frac{A_0}{1+(j\omega/\omega_2)}$ wherein $A_0 = 1000$, $\omega_2 = 10^4$ rad/s. Find the feedback factor which will raise the upper corner frequency ω_2 to 10^5 rad/s. What is the corresponding gain of the amplifier? Find also the gain bandwidth product in this case. ***(MQP '18 – 4M)***
19. Design a RC phase shift oscillator for a frequency of 1 kHz. Draw the circuit diagram with designed values. ***(Jul '19 – 6M)***
20. The frequency sensitivity arms of the Wein bridge oscillator uses $C_1 = C_2 = 0.01\ \mu F$ and $R_1 = 10\ k\Omega$ while R_2 is kept variable. The frequency is to be varied from 10 kHz to 50 kHz by varying R_2. Find the minimum and maximum values of R_2. ***(MQP '18 – 4M)***
21. An astable multivibrator circuit has $R_1 = 6.8\ k\Omega$, $R_2 = 4.7\ k\Omega$, $C = 0.1\ \mu F$. Calculate frequency of oscillation and duty cycle. ***(Sep '20 – 6M)***

References

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