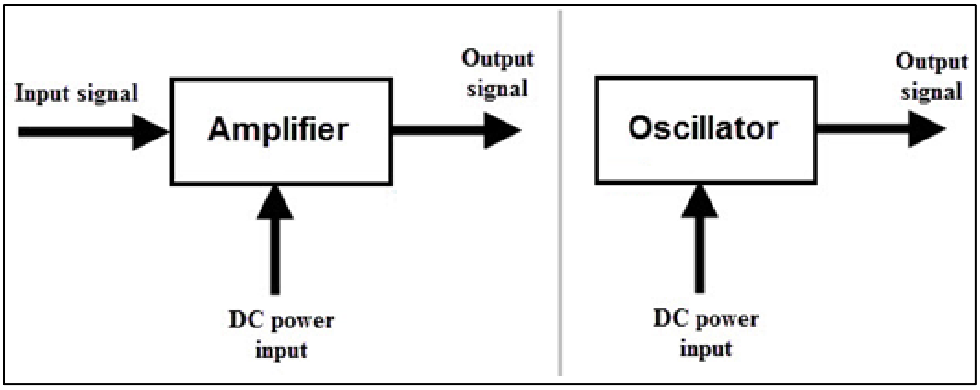
Unit 03: Wave Generators

A] Transistorized Oscillators
1. **Barkhausen Criterion**
2. **R-C Phase Shift Oscillator**
3. **Transistor Crystal oscillator**

B] Timer IC 555
1. **Block diagram and its working**
2. **Astable multivibrator**
3. **Monostable multivibrator**

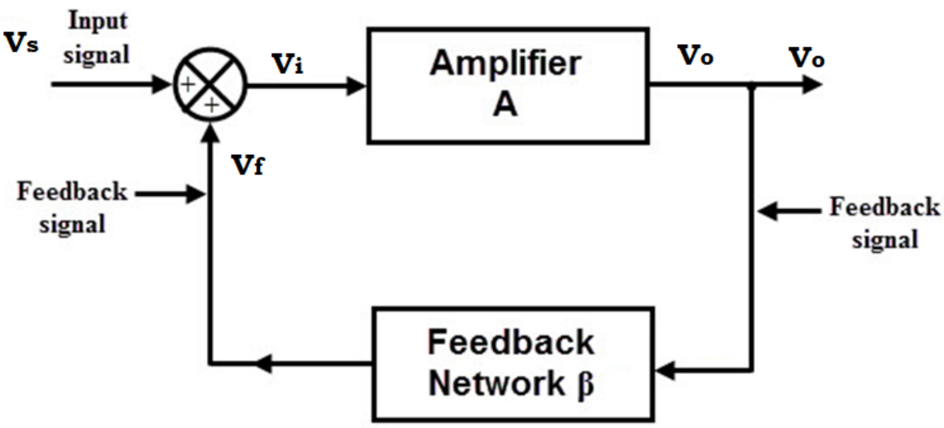
What is an Oscillator?

An electronic circuit used to generate the output signal with constant amplitude and constant desired frequency is called as an Oscillator. It is also called as a Waveform Generator which incorporates both active and passive elements. The primary function of an oscillator is to convert DC power into a periodic sinusoidal signal or AC signal.



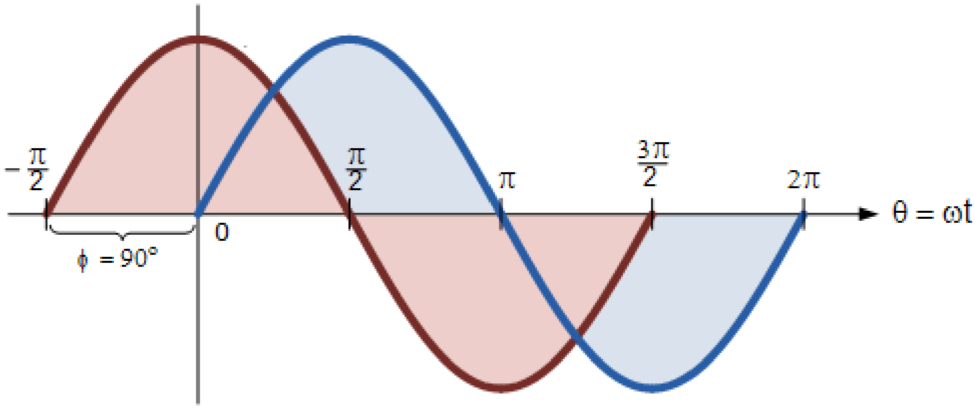
- An oscillator does not require any external input signal to produce sinusoidal or other repetitive waveforms of desired magnitude and frequency at the output.
- In case of amplifiers, the energy conversion starts as long as the input signal is present at the input, i.e., amplifier produces an output signal whose frequency or waveform is similar to the input signal but magnitude or power level is generally high. The output signal will be absent if there is no input signal at the input.
- In contrast, to start or maintain the conversion process an oscillator does not require any input signal. As long as the DC power is connected to the oscillator circuit, it keeps on producing an output signal with frequency decided by components in it.
- Figure below shows basic building blocks of positive feedback amplifier or oscillator circuit. Gain of the circuit with feedback is given as:

$$\text{Gain} = \frac{V_o}{V_s} = \frac{A}{1 - A\beta}$$



The Concept of Phase Shift:

The displacement of one periodic waveform with respect to another of the same frequency is called as Phase Shift. Generally, it occurs between the input and output of a signal-processing device, such as an electronic amplifier or filter, caused by the processing of the signal. Phase shift is measured as the angle (in degrees/radians)



Barkhausen Criterion:

Oscillators work on the principle of positive feedback or regenerative feedback. That is, a fraction of output (from amplifier) is taken and added back to input with proper magnitude and phase. By doing so, output regenerates even though input is removed. However, to make it happen, Barkhausen's criterion has to be satisfied which states:

1) Magnitude of overall gain around the loop should be unity [i.e., $|A\beta|=1$]
In practical terms, it means that the product of gain offered by the amplifier and attenuation offered by the feedback network is unity. Note that amplifier is an active network which offers gain whereas feedback network is normally a passive resistive network which offers attenuation.

2) Overall phase shift around loop should be either zero or multiple of 360^{o} Normally, Common Emitter amplifier gives 180^{o} phase shift and another 180^{o} phase shift is given by feedback network.

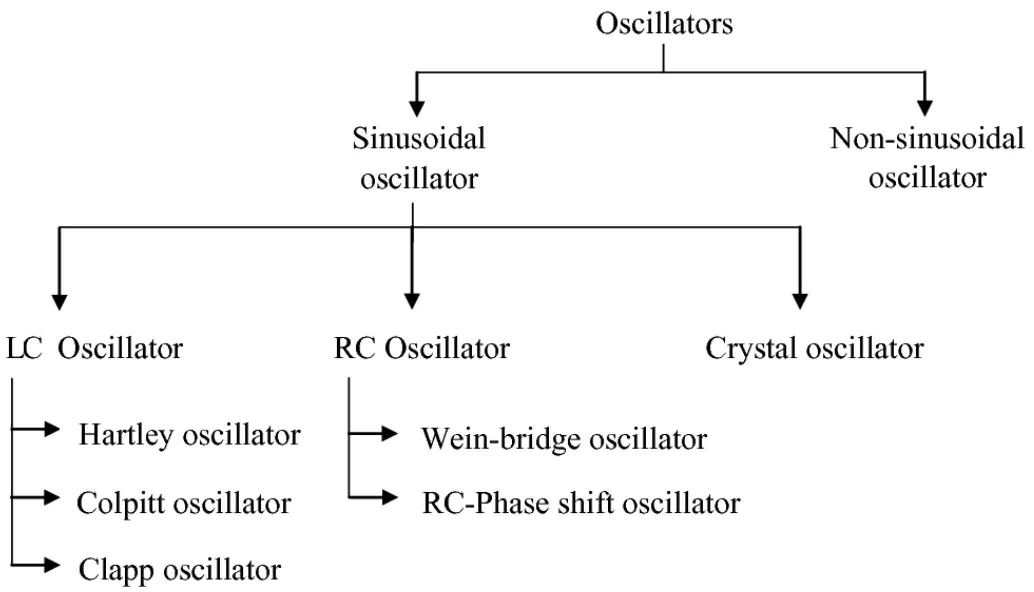
Types of Transistorized Oscillators:

Oscillators can be classified on the basis of components used in circuit as:
1] RC Oscillators [Resistor, Capacitors are used]: Audio Frequency Oscillators
2] LC Oscillators [Inductor, Capacitors are used]: Radio Frequency Oscillators
3] Crystal Oscillators

RC Oscillators:

These oscillators use resistors and capacitors to provide the phase-shift required by the feedback signal. These are used to generate low or radio frequency signals. Thus, they are also known as Audio Frequency Oscillators. Two important RC Oscillators are:

1. RC Phase Shift Oscillator
2. Wien bridge oscillator



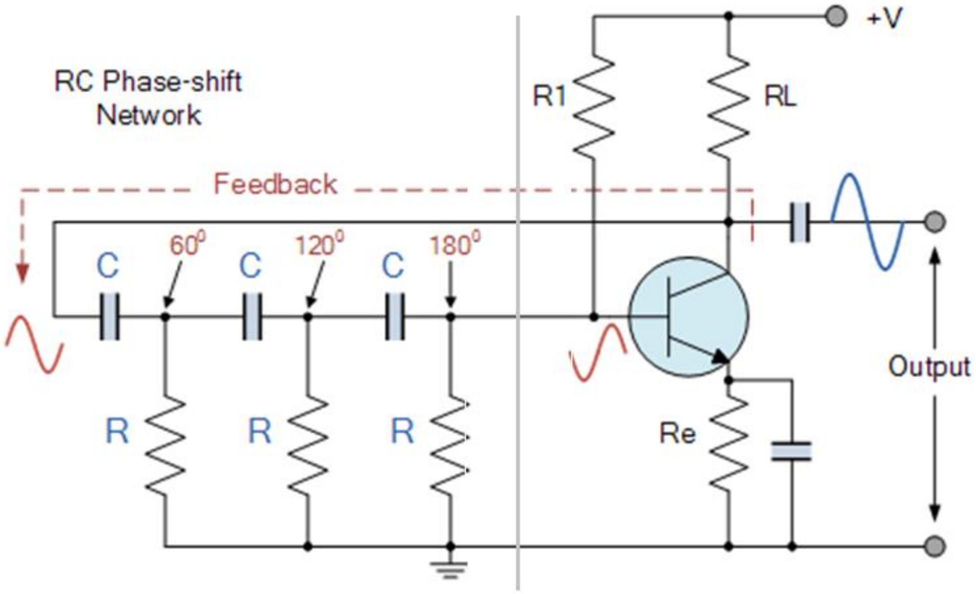
RC Phase Shift Oscillator

The following figure shows circuit diagram of RC Phase Shift Oscillator. It consists of RC Phase shift network connected in feedback path [i.e., between collector and base]. Transistor is connected so that it is working as an amplifier. RC phase shift network consists of three identical RC sections. A coupling capacitor is connected at output and bypass capacitor is connected across emitter resistor. Both capacitors are used to block DC signal & allow AC signal.

Working of RC Phase Shift Oscillator

- As three RC sections are used as feedback network, the oscillator is called as RC phase shift oscillator. In order to work as an oscillator, the circuit needs to satisfy Barkhausen’s Criterion.

- When the circuit is switched ON, some part of output is applied to the input section. This part gets amplified with help of amplifier but introduces 180^o phase shift.
- In order to obtain sustained oscillations, the total phase shift should be 360^o. Thus, three RC sections contribute 60^o phase shift each. Hence, phase shift introduced by RC sections is $60^o + 60^o + 60^o = 180^o$.
- Finally, total 360^o phase shift is present between input and output and the circuit starts to oscillate with constant frequency.



The frequency of oscillations is decided by the value of resistor and capacitor used in the RC section. It is given by the expression,

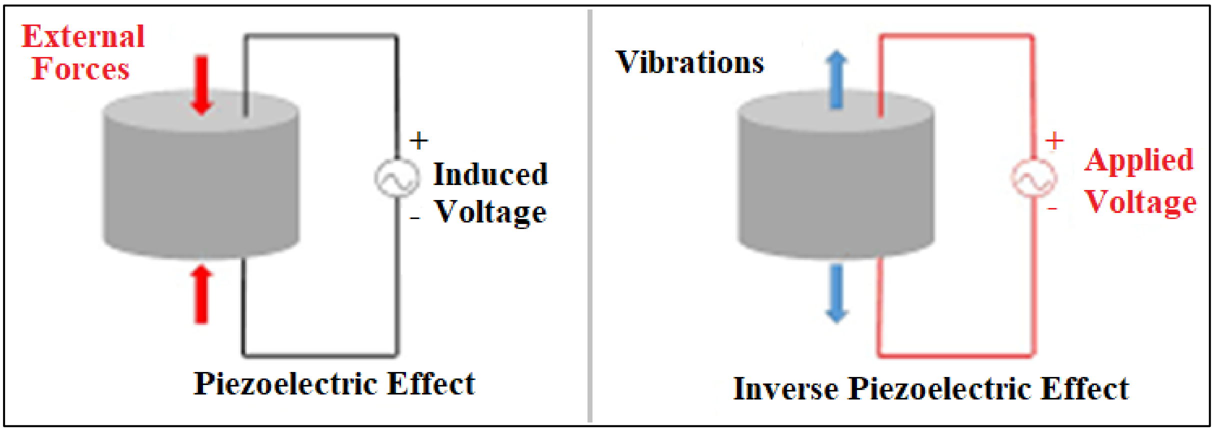
$$f = \frac{1}{2\pi\sqrt{6}\,RC}\ \text{Hz}$$

NOTE: Since, the resistor-capacitor combination in this circuit also acts as an attenuator producing a total attenuation of 1/29 (Vi/Vo = β) across the three stages. Thus, voltage gain of the amplifier must be sufficiently high enough to overcome these RC losses. Hence, the amplifier gain must be equal to, or greater than, 29.

Piezoelectric Effect

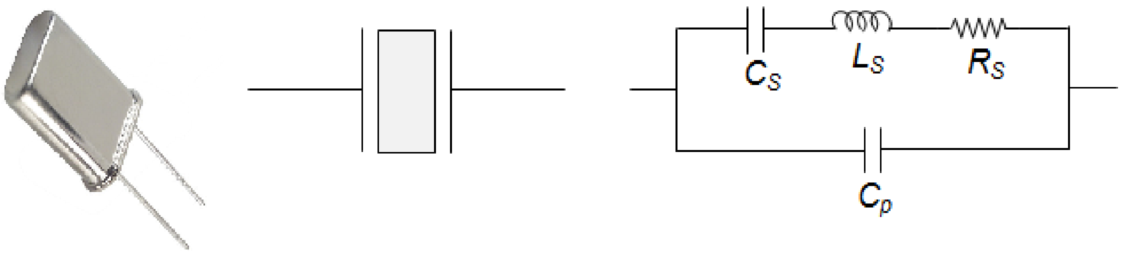
- **Piezoelectric Effect:** When certain crystalline materials (such as Quartz, Rochelle Salt and Tourmaline) are compressed or placed under mechanical strain to vibrate, then they produce an AC voltage.

- **Inverse Piezoelectric Effect:** When an AC voltage is applied across certain crystalline materials (such as Quartz, Rochelle Salt and Tourmaline), they start vibrating with the frequency of applied voltage.



Crystal Oscillator

- Crystal oscillators operate on the principle of Inverse Piezoelectric Effect in which an alternating voltage applied across the crystal surfaces causes it to vibrate at its natural frequency. These oscillators are usually made of Quartz crystal, Rochelle salt and Tourmaline etc.
- In crystal oscillators, the crystal is suitably cut and mounted between two metallic plates as whose electrical equivalent is shown in figure.
- In reality, crystal behaves like a series RLC circuit, formed by components: low-valued resistor R_S, large-valued inductor L_S, small-valued capacitor C_S which will be in parallel with the capacitance of its electrodes C_p.



Quartz Crystal   Equivalent Electric Circuit

Due to the presence of C_p, the crystal will resonate at two different frequencies:

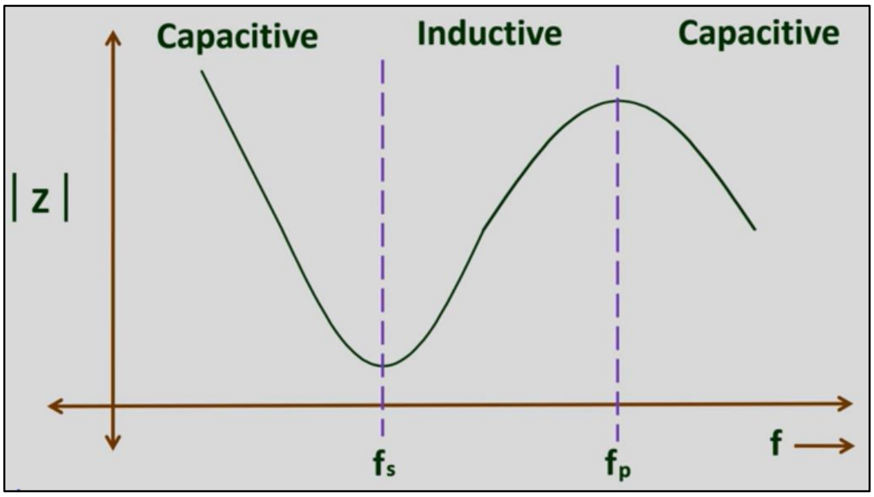
1. **Series Resonant Frequency, f_s** which occurs when the series capacitance C_S resonates with the series inductance L_S. At this stage, the crystal impedance will be the least and hence the amount of feedback will be the largest. Mathematical expression for the same is given as:

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}} \text{ Hz}$$

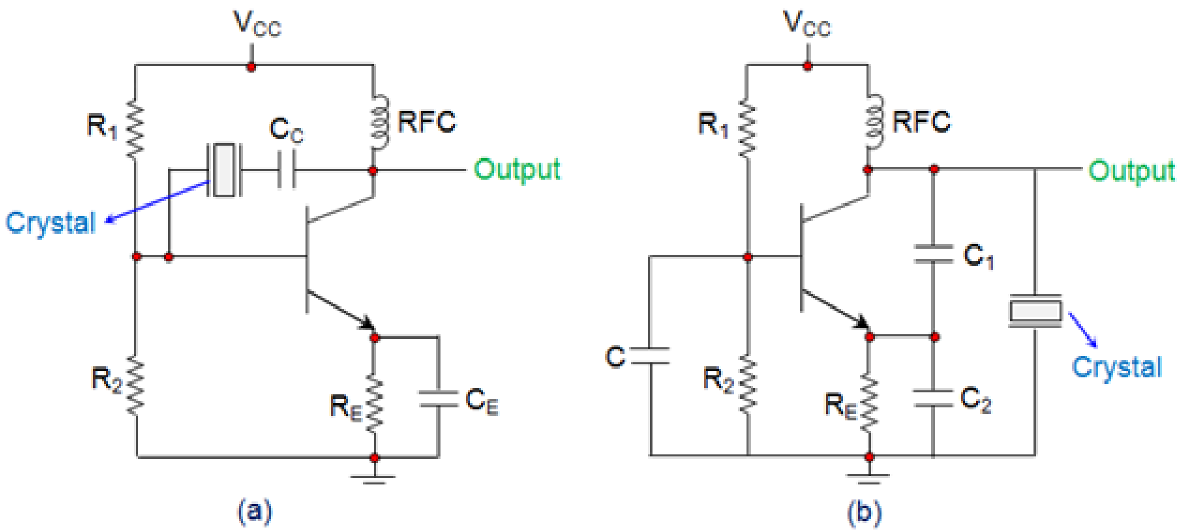
2. **Parallel Resonant frequency, f_p** which is exhibited when the reactance of the L_SC_S equals the reactance of the parallel capacitor C_p (i.e. L_S and C_S resonate with C_p). At this instant, the crystal impedance will be the highest and thus the feedback will be the least. Mathematically it can be given as:

$$f_p = \frac{1}{2\pi\sqrt{L_s(C_s||C_p)}}\ \text{Hz}$$

The behaviour of the crystal will be capacitive both below f_s and above f_p. However, for the frequencies which lie in-between f_s and f_p, crystal's behavior will be inductive. Hence, a crystal can be viewed as a combination of series and parallel tuned resonance circuits due to which one needs to tune the circuit for any one among these two. Moreover, it is to be noted that $f_p$will be higher than f_s.



Crystal oscillators can be designed by connecting the crystal into the circuit such that it offers low impedance when operated in series-resonant mode (Figure a) and high impedance when operated in anti-resonant or parallel resonant mode (Figure b).



Crystal Oscillator Operating in (a) Series Resonance (b) Parallel Resonance

- In the circuits shown, the resistors R_1 & R_2 form the voltage divider network while the emitter resistor R_E stabilizes the circuit. Further, C_E acts as an AC bypass capacitor while the coupling capacitor C_C is used to block DC signal.
- The capacitors C_1 , C_2 form the capacitive voltage divider network in the case of Fig (b). In addition, there is also a Radio Frequency Coil (RFC) in the circuits which provides the DC bias as well as frees the output from being affected by the AC signal on the power lines.
- On supplying the power to the oscillator, the amplitude of the oscillations in the circuit increases until loop gain equals to unity. Further, the frequency will self-adjust so as to facilitate the crystal to present a reactance to the circuit such that the Barkhausen's phase requirement is fulfilled.
- The typical operating range of the crystal oscillators is 40 KHz -100 MHz.

Merits of Crystal Oscillator

- The frequency of oscillations generated is unaffected by the variations in supply voltage and transistor parameters.
- Crystal oscillators exhibit high Q-factor
- It has excellent frequency stability
- Crystal oscillators are compact in size and are of low cost
- They are extensively used in microcontrollers, GPS, computers & mobiles

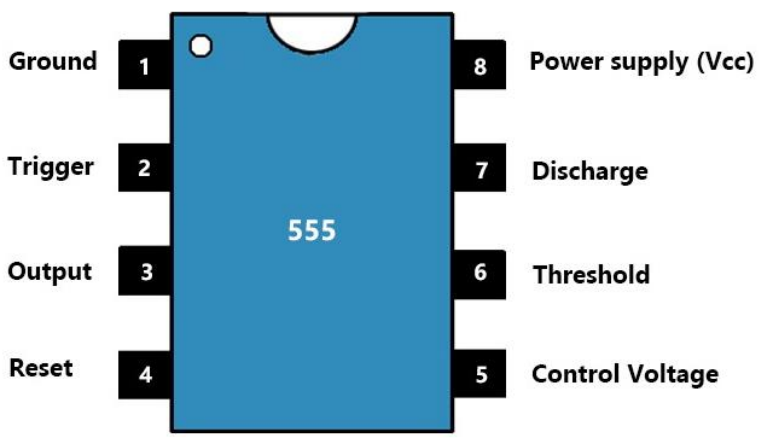
Demerits of Crystal Oscillator

- When too much of power delivered to the crystal, then the crystal leads to unstable resonant frequency.
- Its o/p waveform might be distorted due to degradation in its performance.
- It can even result in the destruction of the device (crystal) due to overheat.

Timer IC 555

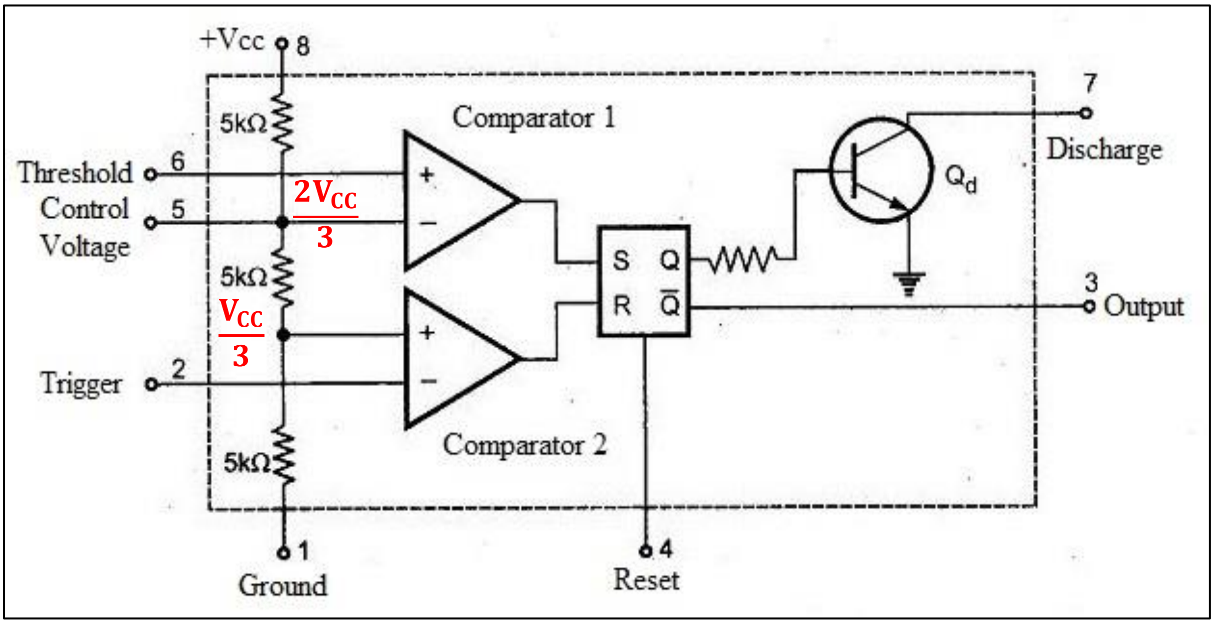
The IC 555 is the most versatile IC introduced by Signetics Corporation in early 1970. It is used in a variety of applications such as timer, delay, pulse generation and oscillators.

555 Timer IC - PIN Diagram



Block Diagram of IC 555

The functional block diagram is shown in Figure. A block diagram consists of: a voltage divider network formed due to three equal resistors, two comparators, a flip-flop, a discharge transistor and an output stage.



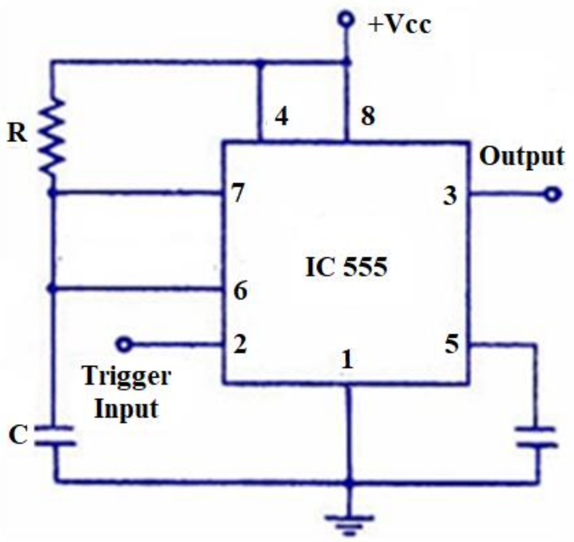
- The voltage divider consists of three identical 5 k*Ω* resistors which create two reference voltages at 1/3 and 2/3 of the supplied voltage (Vcc).
- Next are the two comparators. A comparator is a circuit element that compares two analog input voltages at its positive (non-inverting) and negative (inverting) input terminal.
- If the input voltage at the positive terminal is higher than the input voltage at the negative terminal the comparator will output 1.
- Vice versa, if the voltage at the negative input terminal is higher than the voltage at the positive terminal, the comparator will output 0.
- The first comparator negative input terminal is connected to the 2/3 reference voltage at the voltage divider and the external CONTROL VOLTAGE pin, while the positive input terminal to the external THRESHOLD pin.
- On the other hand, the second comparator negative input terminal is connected to the TRIGGER pin, while the positive input terminal to the 1/3 reference voltage at the voltage divider.
- So using the three pins (Trigger, Threshold and Control) we can control the output of the two comparators which are then fed to the R and S inputs of the flip-flop.
- Flip-flop has two outputs which are complementary to each other Q & $\overline{\text{Q}}$. When R=1, $\text{Q} = 0$ & $\overline{\text{Q}} = 1$ and when S=1 then $\text{Q} = 1$ & $\overline{\text{Q}} = 0$.
- Additionally the flip-flop can be reset via the external pin called RESET which can override the two inputs, thus reset the entire timer at any time.
- The ($\overline{\text{Q}}$) output of the flip-flip is nothing but OUTPUT pin. The output of the flip-flip is also connected to a transistor that connects the DISCHARGE pin to ground.

Pin Configuration of IC 555

PIN 1: GROUND All voltages are measured with respect to this terminal
PIN 2: TRIGGER
The IC 555 has two comparators. The voltage divider consists of three equal resistances. Due to voltage divider, the voltage of non-inverting terminal of comparator 2 is fixed to Vcc/3. The inverting input of comparator 2 is Trigger input. When trigger input is slightly less than Vcc/3 the comparator 2 goes high. This output is given to reset input of flipflop which resets the flipflop.
PIN 3: OUTPUT The complementary signal output ($\overline{Q}$) of flipflop is the output of IC 555.
PIN 4: RESET
This is an interrupt to the timing device. When pin 4 is grounded, it stops the working of device and makes it OFF.
PIN 5: CONTROL VOLTAGE
This is inverting pin of comparator 1. The voltage divider holds the voltage of this input at 2/3 Vcc.
PIN 6: THRESHOLD
This is non-inverting pin of comparator 1. The external voltage is applied to this pin. When this voltage becomes more than 2/3 Vcc, the comparator 1 goes to high output which will set the flipflop.
PIN 7: DISCHARGE
This pin is connected to the collector of discharge transistor Q_d. When Q is low and transistor is OFF (cut-off state) and it acts as open circuit. When Q is high and transistor is ON (saturation state) and it acts as short circuit.
PIN 8: +Vcc This is supply voltage pin to the IC 555.

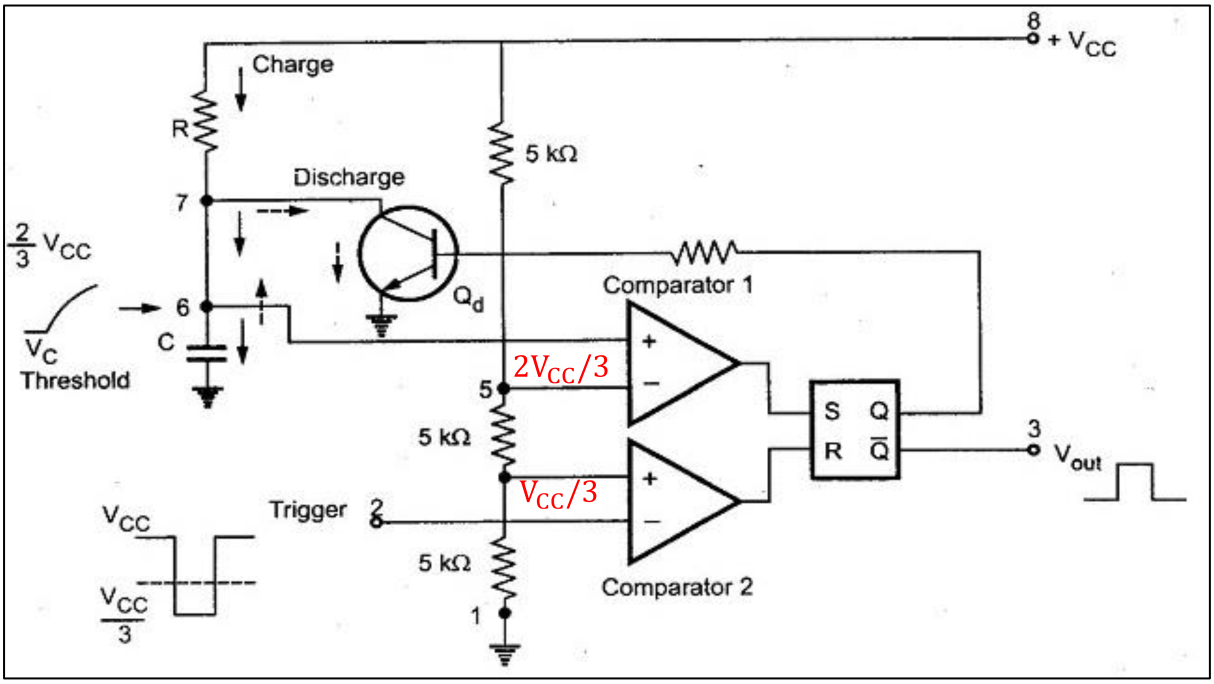
Monostable Multivibrator using IC 555

The IC 555 timer can be operated as a Monostable Multivibrator by connecting an external resistor and a capacitor as shown in following figure: It has **one stable state (mono)** and one quasi-stable (partially stable) state. When trigger is applied, it produces a pulse at the output and returns back to its stable state. The duration of pulse depends on the values of R and C. Hence, it is also called as Pulse Generator. It has another name called as One-shot Multivibrator.



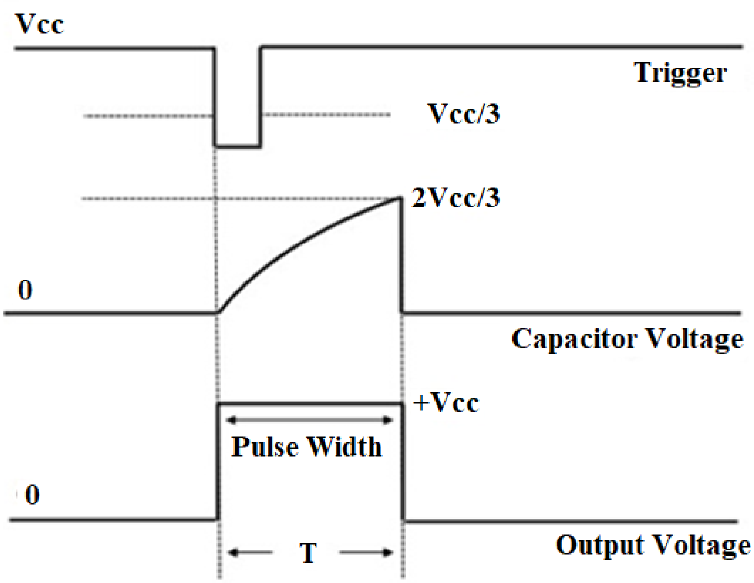
WORKING:

The flipflop is initially set i.e. Q is high. This drives transistor Qd in saturation. The capacitor discharges completely and voltage across it is zero.



The output at pin 3 is low. When a trigger input [a low going pulse] is applied, then circuit state remains unchanged till trigger voltage is greater than 1/3 Vcc. When it becomes less than 1/3 Vcc, then comparator 2 output goes high. This resets the flipflop so Q goes low and $\overline{Q}$ goes high. Low Q makes transistor Q_d OFF. Hence, capacitor starts charging through resistor R. Thus, voltage across capacitor increases exponentially. This voltage is nothing but the threshold voltage at pin 6.

When this voltage becomes more than 2/3 V_{CC}, then comparator 1 output goes high. This sets flipflop i.e. Q becomes high and $\overline{Q}$ is low. This high Q drives the transistor Q_d in saturation. Thus, capacitor C quickly discharges to ground. So, it can be noted that V_{out} at pin 3 is low at start, when trigger is less than 1/3 V_{CC} it will become high and when threshold is greater than 2/3 V_{CC} again it becomes low till the next trigger pulse occurs.



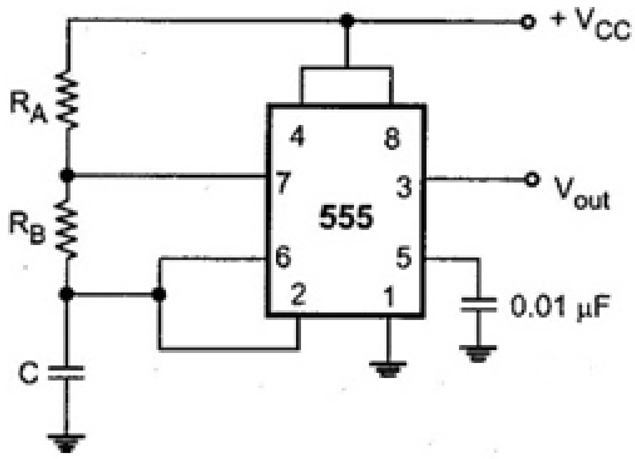
The width of produced pulse depends on time constant RC and is given by following expression,

$$T = 1.1 * R * C$$

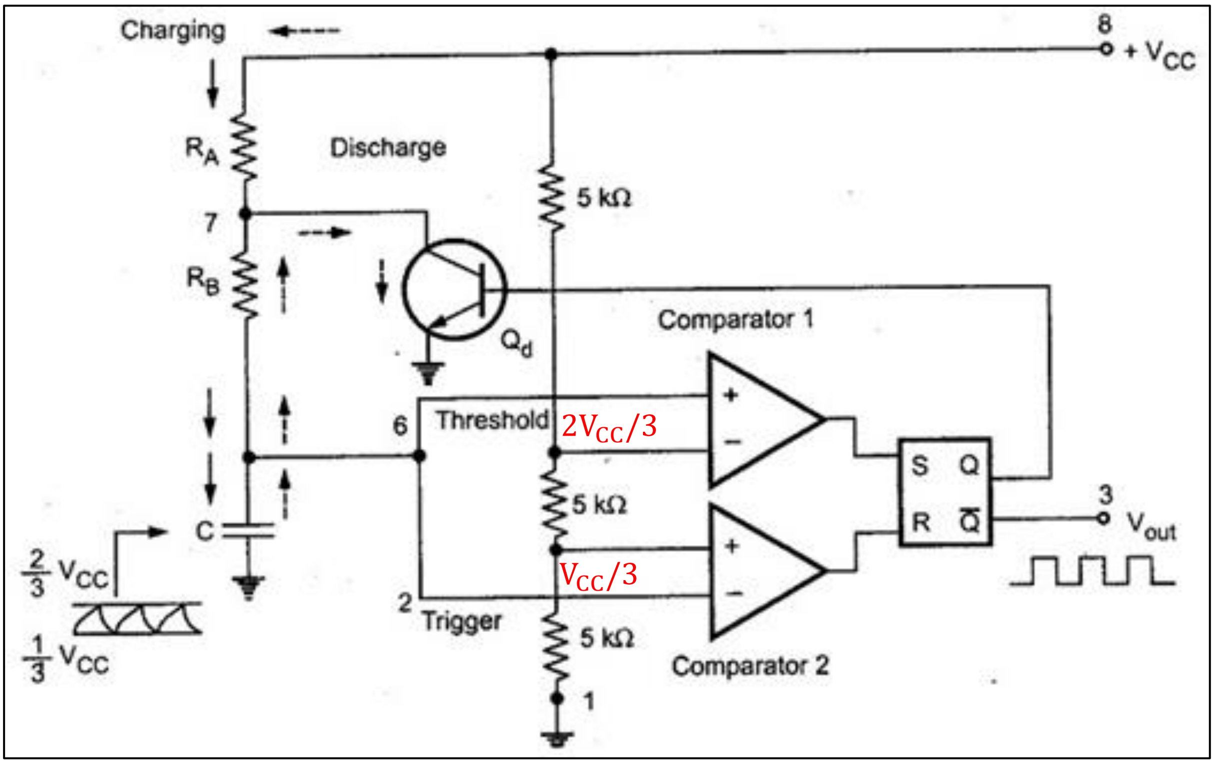
Figure shows different waveforms of Monostable Multivibrator

Astable Multivibrator using IC 555

The following figure shows IC 555 connected as an astable multivibrator. The threshold input (pin 6) is connected to the trigger input (pin 2). Two external resistors R_A, R_B and capacitor C is used in the circuit. The circuit has No Stable state. Hence, it is called as Astable Multivibrator. It changes its state alternatively. Hence, also called as Free Running Oscillator.



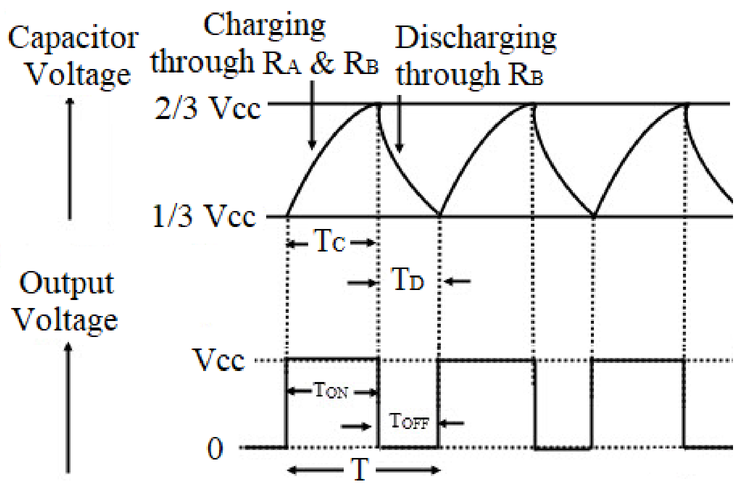
WORKING: The flipflop is initially set i.e. Q is high. This drives transistor Qd in saturation and capacitor gets discharged.



The capacitor voltage is nothing but TRIGGER VOLTAGE. So while discharging, when it becomes less than 1/3 Vcc, comparator 2 output goes high. This will reset the flipflop. Hence, Q goes low and $\overline{Q}$ goes high. The low Q makes transistor OFF. Thus, capacitor starts charging through the external resistances R_A, R_B and C. The charging path is shown in thick arrows in figure. The charging time constant is $(R_A + R_B)C$.

Now, the capacitor voltage is also THRESHOLD VOLTAGE. While charging, capacitor voltage increases (i.e. threshold voltage increases). When it exceeds 2/3 Vcc, the comparator 1 output goes high which sets the flipflop. The flipflop output Q becomes high and output at pin 3 i.e. $\overline{Q}$ becomes low. High Q drives transistor into saturation and capacitor starts discharging through resistance R_B and transistor Q_d. This path is shown by dotted arrows in fig. Thus, discharging time constant is R_BC.

While discharging, when capacitor voltage becomes less than Vcc/3, comparator 2 output goes high, resetting flipflop. This cycle repeats and we get rectangular wave at output. Figure shows o/p waveforms of Astable Multivibrator.



The Charging time of capacitor is given by,

$$T_C = 0.693(R_A + R_B)C$$

While discharge time is given by, $T_D = 0.693R_BC$

Thus, time for one complete cycle is, $T = T_C + T_D$

$$\therefore T = 0.693(R_A + 2R_B)C$$

Frequency of oscillations is given by,

$$f = \frac{1.44}{(R_A + 2R_B)C} \text{ Hz}$$

Duty Cycle: It is defined as ratio of ON time (T_{ON}) to the total time period [$T = T_{ON} + T_{OFF}$] of waveform. For symmetric wave, its value is 50%.

$$D = \frac{T_{ON}}{T} \times 100\% = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times 100\% \quad \text{or} \quad D = \frac{(R_A + R_B)}{(R_A + 2R_B)} \times 100\%$$

Numerical:

Q.1] Find out the pulse-width of the wave generated by a monostable multivibrator with R = 68 kΩ and C = 0.1 µF.

Solution ➔ The pulse width expression for monostable multivibrator is given by,

$$T = 1.1 \times R \times C$$
$$T = 1.1 \times 68\text{ k}\Omega \times 0.1 \times 10^{-6}$$
$$T = 1.1 \times 68 \times 10^{3} \times 0.1 \times 10^{-6}$$
$$\therefore T = 7.48 \times 10^{-3}\text{ sec} = 7.48\text{ msec}$$

Q.2] The timer IC is used in monostable mode where R = 10 kΩ and output pulse width is T = 2.2 ms. Determine the value of Capacitor.

Q.3] An Astable Multivibrator is constructed using IC 555 and following components, RA = 1 kΩ, RB = 2 kΩ and capacitor C = 10 μF. Calculate:

1. **Charging time**
2. **Discharging time**
3. **Output frequency**
4. **Duty cycle of the output waveform.**

Solution ➔

1. The Charging time of capacitor is given by,

$$T_C = 0.693(R_A + R_B)C$$
$$T_C = 0.693(1k\Omega + 2k\Omega)10 \times 10^{-6}$$
$$T_C = 0.693 \times 3 \times 10^3 \times 10 \times 10^{-6}$$
$$T_C = 20.8 \times 10^{-3}\ \text{sec} = 20.8\ \text{msec}$$

2. Discharging time of capacitor is given by,

$$T_D = 0.693R_BC$$
$$T_D = 0.693 \times 2k\Omega \times 10 \times 10^{-6}$$
$$T_D = 0.693 \times 2 \times 10^3 \times 10 \times 10^{-6}$$
$$T_D = 13.86 \times 10^{-3}\ \text{sec} = 13.86\ \text{msec}$$

3. Frequency of oscillations is given by,

$$f = \frac{1.44}{(R_A + 2R_B)C} = \frac{1.44}{(1k\Omega + 2 * 2k\Omega)10 \times 10^{-6}}$$
$$f = \frac{1.44}{5 \times 10^3 \times 10 \times 10^{-6}} = \frac{1.44}{5 \times 10^{-2}}$$
$$\therefore f = 28.8\ \text{Hz}$$

4. Duty cycle is given by,

$$D = \frac{(R_A + R_B)}{(R_A + 2R_B)} \times 100\%$$
$$D = \frac{1k\Omega + 2k\Omega}{1k\Omega + 2 * 2k\Omega} \times 100\%$$
$$D = \frac{3k\Omega}{5k\Omega} \times 100\%$$
$$\text{Duty cycle, } D = 60\%$$

Q.4] Design a IC 555 timer as an Astable Multivibrator with an output signal frequency of 800 Hz and 60 percent duty cycle.

Solution ➔ The percent duty cycle is given by,

$$D = \frac{(R_A + R_B)}{(R_A + 2R_B)} \times 100 = 60$$
$$(R_A + R_B) = 0.6(R_A + 2R_B)$$
$$R_A + R_B = 0.6R_A + 1.2R_B$$
$$0.4\ R_A = 0.2\ R_B$$
$$\therefore R_B = 2R_A$$

Output frequency is given by,

$$f = \frac{1.44}{(R_A + 2R_B)C}$$

Substituting f = 800 Hz, $R_B = 2R_A$ and C = 0.01 μF (assumed value) in above equation, we get,

$$800 = \frac{1.44}{(R_A + 2 * 2R_A)0.01\mu F}$$

$$800 = \frac{1.44}{5R_A \times 0.01\times10^{-6}}$$

$$\therefore R_A = \frac{1.44}{5 \times 800 \times 0.01\times10^{-6}}$$

$$R_A = \frac{1.44}{4 \times 10^3\times10^{-8}} = 0.36 \times 10^5 = 36\ k\Omega$$

Also, we know that, $R_B = 2R_A = 2 \times 36\ k\Omega = 72\ k\Omega$

Thus, astable multivibrator with frequency = 800 Hz & Duty cycle = 60% can be designed using following components in the circuit:

$R_A = 36\ k\Omega$, $R_B = 72\ k\Omega$ and C = 0.01 μF.

Q.5] Design an Astable Multivibrator for $T_{ON} = 3$ ms and $T_{OFF} = 1$ ms.

Solution ➔ Discharging time of capacitor is given by,

$$T_{OFF} = T_D = 0.693 * R_B * C$$

$$\text{i.e.,}\quad 1\ \text{ms} = 0.693 * R_B * C$$

Assume value of C = 1 μF, thus by substituting this value in above equation, we get

$$1 \times 10^{-3} = 0.693 * R_B * 1 \times 10^{-6}$$

$$R_B = \frac{1}{0.693} \times 10^3 = 1.44\ k\Omega$$

The Charging time of capacitor is given by,

$$T_{ON} = T_C = 0.693(R_A + R_B)C$$

Substituting values of T_{ON}, R_B and C we get..

$$3\ \text{ms} = 0.693(R_A + R_B)1\ \mu F$$

$$3 \times 10^{-3} = 0.693(R_A + R_B)1 \times 10^{-6}$$

$$R_A + R_B = \frac{3 \times 10^{-3}}{0.693 \times 10^{-6}} = 4.32\ k\Omega$$

$$\therefore R_A = (4.32 - 1.44)k\Omega = 2.88\ k\Omega$$

Thus, astable multivibrator for $T_{ON} = 3$ ms and $T_{OFF} = 1$ ms can be designed using following components in the circuit:

$R_A = 2.88\ k\Omega$, $R_B = 1.44\ k\Omega$ and C = 1 μF

Important Questions:

1. What is Oscillator? Explain the Barkhausen's criterion in brief.
2. Explain the working of RC Phase shift oscillator with suitable diagram.
3. Discuss working principle of crystal oscillators with suitable diagram. What are its advantages over RC phase shift oscillator?
4. Draw and explain internal block diagram of IC 555.
5. Describe the principle of astable multivibrator. Derive its expression for ON time and OFF time.
6. Explain the working of Monostable multivibrator using suitable circuit diagram.