UNIT – III

MULTIVIBRATORS

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Bi-Stable Multivibrators: Transistor as a Switch, Transistor switching timings, A basic binary circuit-explanation. Fixed-bias transistor binary, self-biased transistor binary, binary with commutating capacitors-analysis, Non-saturated binary–symmetrical triggering, and Schmitt trigger circuit-emitter coupled binary circuit.

Mono-Stable Multivibrator: Basic circuit-collector coupled monostable multivibrator- explanation.

Astable Multivibrator: The collector coupled Astable multivibrator-explanation.

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3.1 Transistor as a Switch

A transistor can be used as a switch. It has three regions of operation. When both emitter-base and collector-base junctions are reverse biased, the transistor operates in the cut-off region and it acts as an open switch.

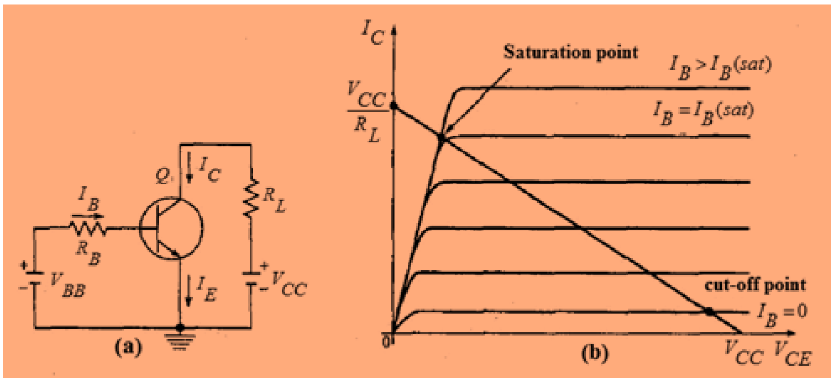

Figure 3.1 (a) Transistor used as a switch, (b) Output characteristics with dc load line

When the emitter-base junction is forward biased and the collector-base junction is reverse biased, it operates in the active region and acts as an amplifier. When both the emitter-base and collector-base junctions are forward biased, it operates in the saturation region and acts as a closed switch. When the transistor is switched from cut-off to saturation and from saturation to cut-off with negligible active region, the transistor is operated as a switch. When the transistor is in saturation, junction voltages are very small but the operating currents are large. When the transistor is in cut-off, the currents are zero (except small leakage current) but the junction voltages are large.

In Figure 3.1 the transistor Q can be used to connect and disconnect the load R_L from the source Vcc. When Q is saturated it is like a closed switch from collector to emitter and when Q is cut-off it is like an open switch from collector to emitter.

During the Cut off state

An ideal transistor has $V_{CE} = V_{CC}$ and $I_C = 0$.

During the Saturation State

An ideal transistor has $V_{CE} = 0$ and $I_C = I_C\,(sat)$.

Generally, from Figure 3.1 (a),

$$I_C \;=\; \frac{V_{CC} - V_{CE}}{R_L} \quad and \quad I_B \;=\; \frac{V_{BB} - V_{BE}}{R_B}$$

Referring to the output characteristics shown in Figure 3.1 (b), the region below the I_B =0 curve is the cut-off region. The intersection of the load line with $I_B = 0$ curve is the *cut-off point.* At this point, the base current is zero and the collector current is negligible. The emitter diode comes out of forward bias and the normal transistor action is lost, i.e, $V_{CE(cut\text{-}off)} = V_{cc}$. The transistor appears like an open switch.

The intersection of the load line with the $I_B - I_{C(sat)}$ curve is called the *saturation point.* At this point, the base current is $I_{B(sat)}$ and the collector current is maximum. At saturation, the collector diode comes out of cut-off and again the normal transistor action is lost, i.e. $I_{C(sat)} = Vcc/R_L$. $I_{B(sat)}$ represents the minimum base current required to bring the transistor into saturation. For $0 < I_B < I_{B(sat)}$, the transistor operates in the active region. If the base current is greater than $I_{B(sat)}$, the collector current approximately equals V_{CC}/I_C and the transistor appears like a closed switch.

Standard Specifications:

In the cut-off region, i.e. for the OFF state

$$\begin{aligned} V_{BE}(cut-off) \;&\leq\; 0V \;\; for \;\; silocon \;\; transistor \\ &\leq\; -0.1V \;\; for \;\; germanium \;\; transistor \end{aligned}$$

In the saturation region i.e. for the ON state

$$\begin{aligned} V_{BE}(sat) \;&:0.7V \;\; for \;\; silocon \;\; transistor \\ &\;\;0.3V \;\; for \;\; germanium \;\; transistor \\ V_{CE}(sat) \;&:0.3V \;\; for \;\; silocon \;\; transistor \end{aligned}$$

$$0.1V \ for \ germanium \ transistor$$

The above values hold good for n-p-n transistors. For p-n-p transistors the above values with opposite sign are to be taken.

Test for Saturation

To test whether a transistor is really in saturation or not evaluate the collector current i_C and the base current i_B independently.

If $i_B > i_B$ (min), where i_B (min) = i_C / h_{FE} (min) -------- > the transistor is really in saturation.

If $i_B \leq i_B$ (min), the transistor is not in saturation.

Test for Cut-Off

To test whether a transistor is really cut-off or not, find its base-to-emitter voltage. If V_{BE} is negative for an n-p-n transistor or positive for a p-n-p transistor, the transistor is really cut-off.

3.2 Transistor Switching Times:

When the transistor acts as a switch, it is either in cut-off or in saturation. To consider the behavior of the transistor as it makes transition from one state to the other, consider the circuit shown in Figure 3.2 (a) driven by the pulse waveform shown in Figure 3.2 (b).

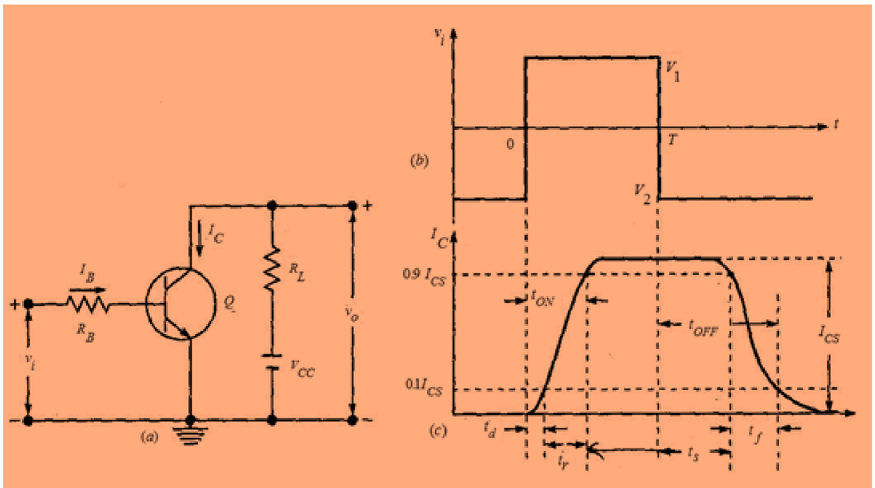

Figure 3.2 (a) Transistor as a switch, (b) input waveform, and (c) the response of collector current versus time.

The pulse waveform makes transitions between the voltage levels V_2 and V_1. At V_2 the transistor is at cutoff and at V_1 the transistor is in saturation. The input waveform v_i is applied between the base and the emitter through a resistor R_B.

The response of the collector current i_c to the input waveform, together with its time relationship to the waveform is shown in Figure 3.2 (c). The collector current does not immediately respond to the input signal. The Switching transistor has a pulse as an input and a pulse with few variations will be the output. There are a few terms that you should know regarding the timings of the switching output pulse. Let us go through them.

Let the input pulse duration = **T**

When the input pulse is applied the collector, current takes some time to reach the steady state value, due to the stray capacitances. The Figure 3.3 explains this concept.

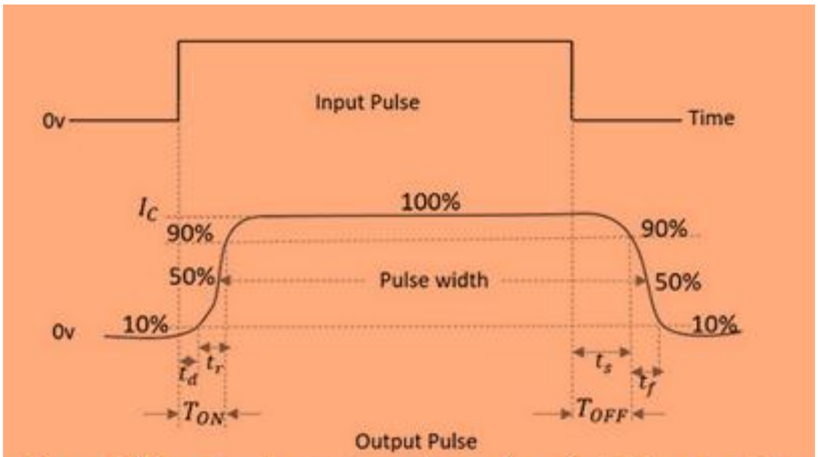

Figure 3.3 Input and output waveforms for a Switching transistor

From the Figure 3.3,

- **Time Delay (t_d):** The time taken by the collector current to reach from its initial value to 10% of its maximum (saturation) value ($I_{Cs} = V_{cc}/R_c$) is called as the **Time Delay t_d**.
- **Rise Time (t_r):** The current waveform has a nonzero rise time $\mathbf{t_r}$, which is the time taken for the collector current to reach from 10% of its initial value to 90% of its final value is called as the **Rise Time t_r**.
- **Turn-on Time (T_{ON}):** The sum of time delay (t_d) and rise time (t_r) is called as **Turn-on time T_{ON}**.

  $T_{ON} = t_d + t_r$
- **Storage Time (t_s)** − The time interval between the trailing edge of the input pulse to the 90% of the maximum value of the output, is called as the **Storage time t_s**.
- **Fall Time (t_f)** − The storage interval is followed by the fall time $\mathbf{t_f}$, which is the time taken for the collector current to reach from 90% of its maximum value to 10% of its initial value is called as the **Fall Time t_f**.

- **Turn-off Time (T_{OFF})** − The sum of storage time (t_s) and fall time (t_f) is defined as the **Turn-off time T_{OFF}**.

  $T_{OFF} = t_s + t_f$

- **Pulse Width (W)** − The time duration of the output pulse measured between two 50% levels of rising and falling waveform is defined as **Pulse Width W**.

3.3 Introduction to Multivibrators:

Multi means many; *vibrator* means oscillator. A circuit which can oscillate at a number of frequencies is called a *multivibrator*. A multivibrator is an electronic circuit used to implement a variety of simple two-state systems such as oscillators, timers and flip-flops. It is characterized by two amplifying devices (transistors, electron tubes or other devices) cross-coupled by resistors or capacitors. The name "multivibrator" was initially applied to the free-running oscillator version of the circuit because its output waveform was rich in harmonics. There are three types of multivibrator circuits depending on the circuit operation:

1. Bistable, in which the circuit is stable in either state. The circuit can be flipped from one state to the other by an external event or trigger.
2. Monostable, in which one of the states is stable, but the other state is unstable (transient). A trigger causes the circuit to enter the unstable state. After entering the unstable state, the circuit will return to the stable state after a set time. Such a circuit is useful for creating a timing period of fixed duration in response to some external event. This circuit is also known as a one shot.
3. Astable, in which the circuit is not stable in either state —it continually switches from one state to the other. It does not require an input such as a clock pulse.

To get a clear idea on the above discussion, let us have a look at the Figure 3.4. Multivibrators are switching circuits that employ positive feedback by cross-coupling the output of one stage to the input of the other stage, such that if one device is ON, the other is OFF. The interchange of states is possible either by the use of external pulses or by internal capacitive coupling. These circuits are used either to generate waveforms of a desired nature or to store binary information. Multivibrators are of three types—astable, monostable and bistable. An astable multivibrator is basically a square-wave generator. A monostable multivibrator generates a gated output (pulse) of a desired duration. A bistable multivibrator stores binary bits.

A transistor Q_1 or Q_2 is said to be in the stable state, if it is either ON or OFF permanently. If the state of the device, say Q_1, changes from ON to OFF, and automatically returns to the ON state after a time duration, the device is said to be in the quasi-stable state for this specified time interval. The devices in this multivibrator will not remain in any one state (ON or OFF) forever. The change of state in the device occurs automatically after a finite time interval, depending on the circuit components employed. Hence, this circuit has two quasi-stable states.

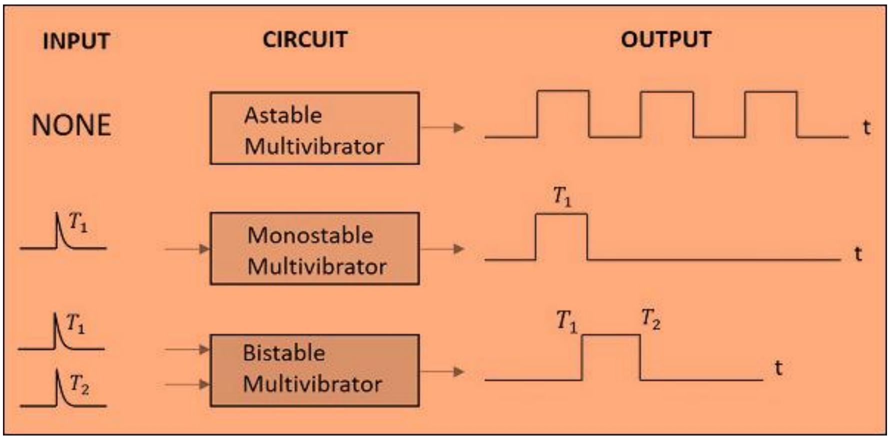

Figure 3.4 Overview of Multivibrators

Multivibrators find applications in a variety of systems where square waves or timed intervals are required. For example, before the advent of low-cost integrated circuits, chains of multivibrators found use as frequency dividers. A free-running multivibrator with a frequency of one-half to one-tenth of the reference frequency would accurately lock to the reference frequency. This technique was used in early electronic organs, to keep notes of different octaves accurately in tune. Other applications included early television systems, where the various line and frame frequencies were kept synchronized by pulses included in the video signal.

History: The classic multivibrator circuit (also called a plate-coupled multivibrator) is first described by H. Abraham and E. Bloch in Publication 27 of the French Ministère de la Guerre, and in Annales de Physique 12, 252 (1919). It is a predecessor of Eccles-Jordan trigger derived from this circuit a year later.

3.4 BISTABLE MULTIVIBRATORS:

A bistable multivibrator is a multivibrator which can exist indefinitely in either of its two stable states and which can be induced to make an abrupt transition from one state to the other by means of external excitation. In a bistable multivibrator both the coupling elements are resistors (dc coupling). The bistable multivibrator is also called a multi, Eccles-Jordan circuit (after its inventors), trigger circuit, scale-of-two toggle circuit, flip-flop, and binary. There are two types of bistable multivibrators:

1. Collector coupled bistable multivibrator

2. Emitter coupled bistable multivibrator

There are two types of collector-coupled bistable multivibrators:

1. Fixed-bias bistable multivibrator

2. Self-bias bistable multivibrator

In the first circuit, two separate sources are used for biasing the devices whereas in the second one self-bias is used to derive the biasing voltage. Besides the two circuits, there is a third variation of bistable mulivibrators, namely, the Schmitt trigger. This circuit, in addition to being used as a bistable, can also be used for other applications like wave shaping, comparators, etc.

A bistable multivibrator has two stable states and this circuit also employs two devices, Q_1 and Q_2. If one device is ON, the other device is required to be OFF. If initially Q_1 is OFF, the voltage at the collector of Q_1 is $V_{C1}= V_{CC}$; and when Q_2 is ON, the voltage at this collector $V_{C2} \approx 0$ V. This is the initial stable state for the bistable multivibrator. The circuit of flipped from one stable state to other (i.e driving into the other stable state in which Q_1 is ON and Q_2 is OFF) by an external trigger. On the application of a trigger, Q_1 switches ON ($V_{C1} \approx 0$ V) and Q_2 switches OFF ($V_{C2} = V_{CC}$) and the states of Q_1 and Q_2 are flipped only when another trigger is applied. If V_{CC} is taken to represent “1” in binary and 0 V represents “0”. So “1” level remains as “1” and “0” level remains as a “0” till the application of a trigger signal. Hence, this type of circuit is used as a one-bit memory element in digital circuits. An array of such circuits can be used to write or store a string of binary digits (0 s or 1 s), called a register. This becomes the basic memory unit in digital computers. This circuit is also known by many names such as binary, flip-flop, scale-of-two circuit and Eccles–Jordan circuit. If the ON device is driven to saturation, the binary is called a saturating binary. If, on the other hand, the ON device is held in the active region, the binary is called a non-saturating binary. An emitter-coupled binary is called a Schmitt trigger. This circuit, in addition to operating as a binary, can also be used as an amplitude comparator and as a squaring circuit.

3.3.1 Fixed-bias Bistable Multivibrators:

The circuit shown in Fig. 3.5 is called a fixed-bias Bistable Multivibrator as two separate dc sources are used to bias the transistors.

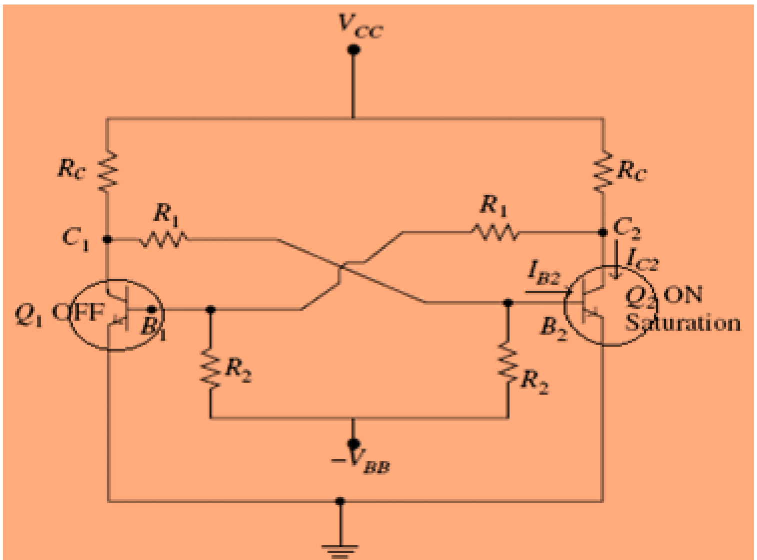

Figure 3.5 Fixed-Bias Bistable Multivibrator

Let assume that initially Q_1 is OFF and Q_2 is ON and in saturation. Then the voltage at the first collector is V_{CC} (the binary equivalent of which is 1) and the voltage at the second collector is $V_{CE(\text{sat})}$ (the binary equivalent being 0). If a negative trigger is applied at the base of the ON device (Q_2), Q_2 goes into the OFF state and its collector voltage rises to V_{CC}. Consequently Q_1 goes into the ON state and its collector voltage falls to $V_{CE(\text{sat})}$. Let us now verify whether Q_1 is really OFF and Q_2 is really ON and in saturation.

To Verify that Q_2 is ON and in Saturation: For this, we have to calculate its base current I_{B2} and its collector current I_{C2} to ensure that the base current is significantly higher than the minimum so that Q_2 is really in saturation. To calculate I_{B2} using Figure 3.6, we begin by assuming that Q_2 is in saturation and Q_1 is OFF and justify the assumption made.

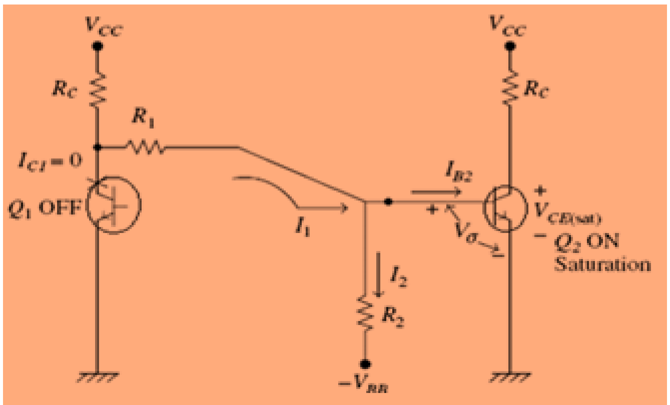

Figure 3.6 The circuit that enables the calculation of I_{B2}

To find I_{B2}, we calculate I_1 and I_2.From the above figure 3.6, we can write

$$I_1 = \frac{V_{CC}-V_{BE(Sat)}}{R_C+R_1} \quad \text{and} \quad I_2 = \frac{V_{BE(Sat)}-(-V_{BB})}{R_2} = \frac{V_{BE(Sat)}+V_{BB}}{R_2}$$

So therefore,

$$I_{B2} = I_1 - I_2 \text{ ---3.1}$$

To calculate I_{C2}, consider the circuit shown in Figure 3.7.

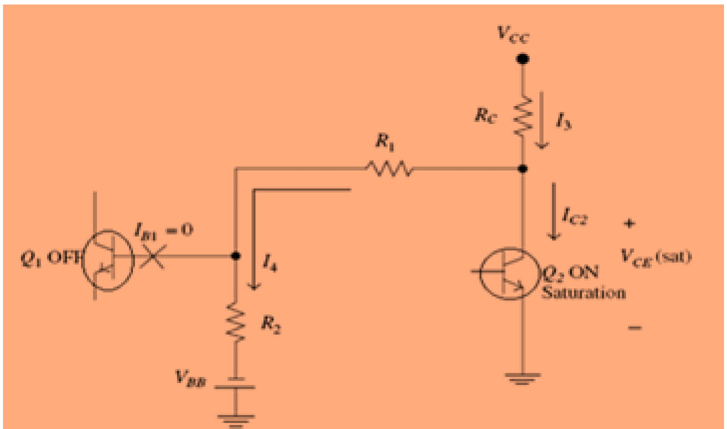

Figure 3.7 The circuit that enables the calculation of I_{C2}

To find I_{C2}, we calculate I_3 and I_4.

From the Figure 3.7 we can write

$$I_3 = \frac{V_{CC} - V_{CE(Sat)}}{R_C} \quad \text{and} \quad I_4 = \frac{V_{CE(Sat)} - (-V_{BB})}{R_1+R_2} = \frac{V_{CE(Sat)}+V_{BB}}{R_1+R_2}$$

$$I_{C2} = I_3 - I_4 \text{ ---3.2}$$

Now find $I_{B2(min)}$ using the relation: $I_{B2(min)} = \frac{I_{C2}}{h_{FE(min)}}$ --------------------------3.3

If $I_{B2} >> I_{B2(min)}$, then Q_2 is in saturation, as assumed.

To Verify that Q_1 is OFF: The transistor Q_1 is OFF if its base–emitter diode is reverse-biased. To verify this, we calculate the voltage V_{B1} at the base of Q_1 using the circuit shown in Figure 3.8 and check whether it reverse-biases the emitter diode or not. If the emitter diode is reverse-biased, the transistor is indeed in the OFF state.

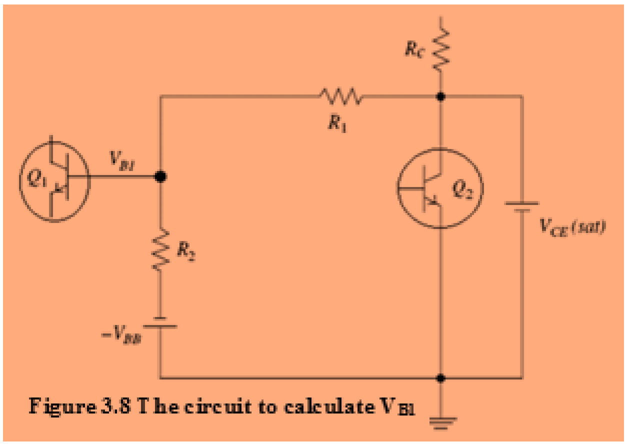

Figure 3.8 The circuit to calculate V_{B1}

The voltage V_{B1} at the base of Q_1 is due to the two sources: $-V_{BB}$ and $V_{CE(sat)}$. Using the superposition theorem:

$$V_{B1} = V_{CE(sat)}\frac{R_2}{R_1+R_2} + (-V_{BB})\frac{R_1}{R_1+R_2} \text{ ---------------------------------------3.4}$$

If the voltage between the base and emitter terminals of Q_1 reverse-biases the base–emitter diode, then Q_1 is OFF and $V_{C1}= V_{CC}$. However, V_{C1} is not exactly V_{CC} as it should be when Q_1 is OFF. Instead, it is smaller than this, because of the cross-coupling network comprising R_1 and R_2. There is a current I_1 through R_1 and R_C. Therefore, the actual voltage at the first collector is not necessarily V_{CC}, but somewhat lower than V_{CC}.

$$V_{C1} = V_{CC} - I_1 R_C \text{ --3.5}$$

The currents and voltages in the initial stable state are calculated, using Eqs. (3.1) to (3.5).

The collector swing, $V_W = V_{C1} - V_{CE(sat)}$

To calculate the stable-state currents and voltages, let us consider Example 3.1.

Example Problem:

Example 3.1: The circuit shown in Figure 3.9 (a) uses an *n-p-n* silicon transistor having $h_{FE(min)} = 50$, $V_{CE(sat)} = 0.3$ V, $V_{BE(sat)} = 0.7$ V, $V_{CC} = 12$ V, $V_{BB} = 12$ V, $R_C = 1\text{k}\Omega$, $R_1 = 10$ kΩ, $R_2 = 20$ kΩ. Calculate the stable-state currents and voltages and also calculate the heaviest load the multivibrator can handle.

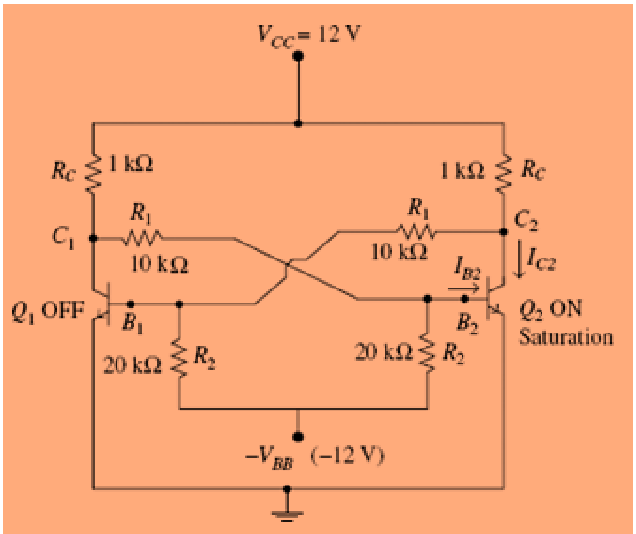

Figure 3.9 (a) The Fixed-Bias Bistable Multivibrator

Solution:

(a) To calculate I_{B2} and I_{C2}:

Consider the Figure 3.9 (b), in which the cross-coupling network from the first collector to the second base is represented, to calculate I_{B2}.

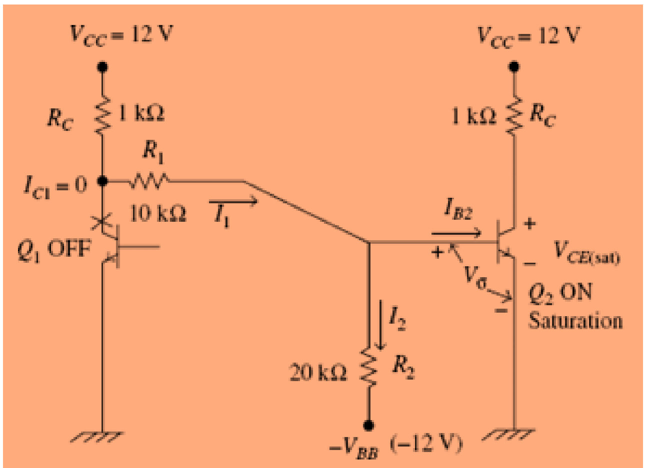

Figure 3.9 (b) The Circuit that Enables the Calculation Of I_{B2}

On the assumption that Q_2 is in saturation and Q_1 is OFF calculations are made and justified. To find I_{B2}, we calculate I_1 and I_2.

Then, $I_{B2} = I_1 - I_2$

$$I_1 = \frac{V_{CC} - V_\sigma}{R_C + R_1} = \frac{12 - 0.7}{1 + 10} = \frac{11.3\text{ V}}{11\text{ k}\Omega} = 1\text{ mA} \qquad I_2 = \frac{V_\sigma - (-V_{BB})}{R_2} = \frac{12.7}{20\text{ k}\Omega} = 0.635\text{ mA}$$

$I_{B2} = I_1 - I_2 = 1\text{mA} - 0.635\text{ mA} = 0.365\text{ mA}$

To calculate I_{C2}, consider the cross-coupling network from the second collector to the first base as shown in Figure 3.9 (c).

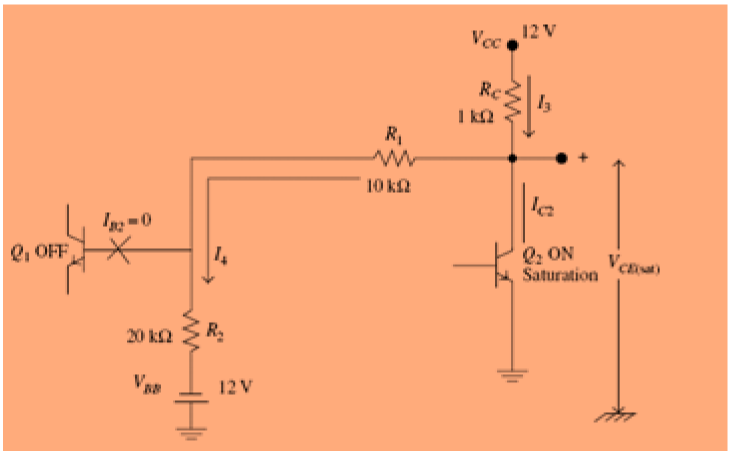

Figure 3.9 (c) The Circuit that Enables the Calculation of I_{C2}

$$I_3 = \frac{V_{CC} - V_{CE(\text{sat})}}{R_C} = \frac{12 - 0.3}{1\text{ K}} = 11.7\text{ mA}$$

$$I_4 = \frac{V_{CE(\text{sat})} - (-V_{BB})}{R_1 + R_2} = \frac{12 + 0.3}{30\text{ K}} = \frac{12.3}{30\text{ K}} = 0.41\text{ mA}$$

$I_{C2} = I_3 - I_4 = 11.7 - 0.41 = 11.29$ mA

- (b) To Verify Q_2 is in saturation:
- $$I_{B2(\text{min})} = \frac{I_{C2}}{h_{FE(\text{min})}} = \frac{11.29\text{ mA}}{50} = 0.226\text{ mA}$$
- For Q_2 to be saturation:
- $I_{B2} \cong 1.5 I_{B2\text{min}}$

  $I_{B2} = 1.5 \times 0.226$ mA $= 0.339$ mA
- Actually, $I_{B2} =$ 0.365 mA, i.e., $I_{B2} >> I_{B2(\text{min})}$. Hence, Q_2 is in saturation. Therefore, $V_{C2} = 0.3$ V, $V_{B2} = 0.7$ V.
- (c) To verify whether Q_1 is OFF or not:
- For verifying whether Q_1 is OFF or not, voltage V_{B1} is calculated, using the circuit shown in Figure 3.9 (d).

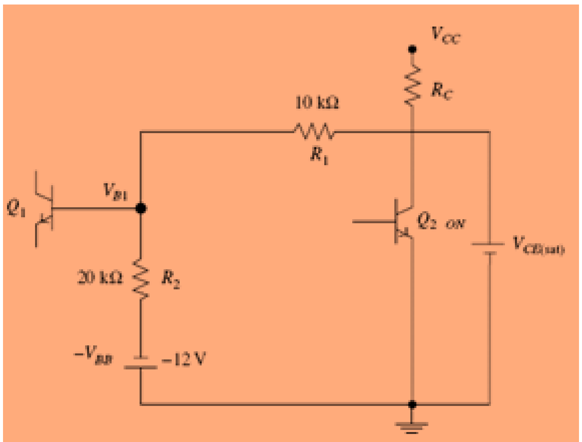

Figure 3.9 (d) The circuit to calculate V_{B1}

To calculate the voltage V_{B1} at the base of Q_1 due to $-V_{BB}$ and $V_{CE(sat)}$ sources, use Eq (3.4).

$$V_{B1} = V_{CE(sat)}\frac{R_2}{R_1 + R_2} + (-V_{BB})\frac{R_1}{R_1 + R_2} = 0.3 \times \frac{20}{30} - 12 \times \frac{10}{30} = 0.2 - 4 = -3.8 \text{ V}.$$

Writing superposition theorem at B_1 we get

$$V_{B1} = V_{CE(sat)}\frac{R_2}{R_1 + R_2} + (-V_{BB})\frac{R_1}{R_1 + R_2}$$

$$= 0.3 \times \frac{20}{30} - 12 \times \frac{10}{30} = 0.2 - 4 = -3.8 \text{ V}.$$

As voltage V_{B1} reverse-biases the emitter diode, Q_1 is OFF and hence,

$V_{C1} = V_{CC} = 12$ V.

However, V_{C1} is not exactly 12 V—as it should be when Q_1 is OFF—but, is smaller than this because of the current I_1 in R_1. The actual voltage at the first collector is,

$V_{C1} = V_{CC} - I_1R_C = 12 - (1\text{mA})(1\text{K}) = 11$ V

Hence, the voltages in the initial stable state are $V_{C1} = 11$ V, $V_{B1} = -3.8$ V, $V_{C2} = 0.3$ V, $V_{B2} = 0.7$ V.

3.3.2 SELF-BIAS BISTABLE MULTIVIBRATOR:

In a self-bias bistable multivibrator, the negative V_{BB} source can be removed by including an emitter resistor R_E in the emitter lead. The voltage drops across R_E is used to derive the other voltage needed. The resistance R_E in a self-bias bistable multivibrator provides stability to the currents and voltages. Here, a self-bias bistable multivibrator in which the ON transistor is driven into saturation is considered. Hence, this circuit is called a saturating bistable multivibrator. One major advantage of a saturating bistable multivibrator is that the power dissipation in devices either when ON or when OFF is so small that transistors with lesser power dissipation capability can be employed. However, its major limitation is larger storage time which tends to reduce the switching speed. Consider the self-bias bistable multivibrator shown in Figure 3.10.

In a fixed bias binary, there are two separate sources, V_{CC} and V_{BB}. Instead two we can design a binary with one power supply using self-bias method.

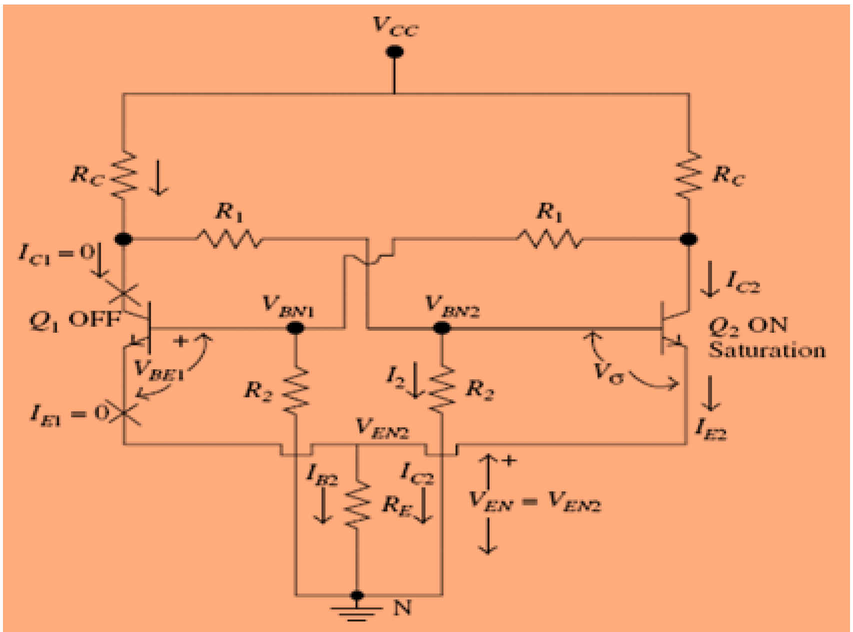

Figure 3.10 The Self-Bias Bistable Multivibrator

Let it be assumed that Q_2 is ON and in saturation, in the initial stable state. As a result, I_{B2} and I_{C2} flow through R_E developing a voltage V_{EN}. The voltage between the base-emitter terminals of Q_1 is V_{BE1} and is given by:

$$V_{BE1} = V_{BN1} - V_{EN} \quad \text{-- 3.6}$$

If this voltage reverse-biases the emitter diode of Q_1, then Q_1 is indeed in the OFF state. To calculate the stable-state currents and voltages, assume that Q_1 is OFF and Q_2 is ON and in saturation. As Q_1 is OFF, $I_{E1} = 0$. To verify whether Q_2 is in saturation or not, the collector and base loops of the circuit are drawn by Thevenizing at the collector and base terminals.

$$V_{thb} = V_{CC} \times \frac{R_2}{R_2 + R_C + R_1} \quad \text{---3.7}$$

and

$$R_{thb} = R_2 \,||\, (R_C + R_1) = \frac{R_2(R_C + R_1)}{R_2 + R_C + R_1} \quad \text{---3.8}$$

$$V_{cth} = V_{CC} \times \frac{(R_2 + R_1)}{R_2 + R_C + R_1} \quad \text{------------------3.9}$$

$$R_{cth} = (R_1 + R_2) \,||\, R_C \quad \text{------------------ 3.10}$$

The base and collector loops of Q_2 are drawn as shown in Figure 3.11.

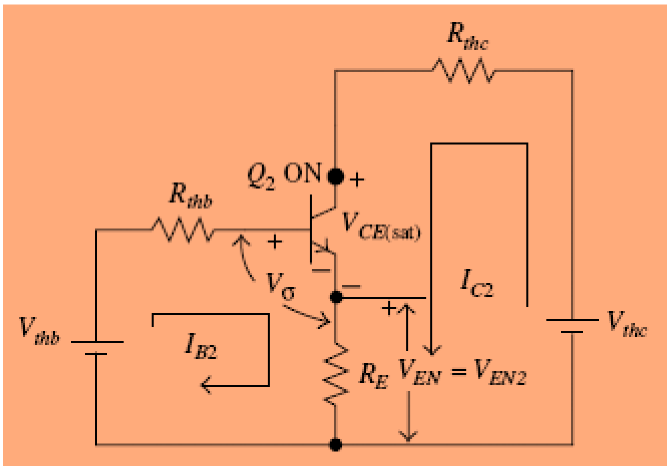

Figure 3.11 The Circuit to Calculate the Base and Collector Currents Of Q_2

Writing the KVL equations of the input and output loops we get:

$$V_{thb} - V_\sigma = I_{B2}(R_{thb} + R_E) + I_{C2}R_E \quad \text{------------------ 3.11}$$

$$V_{thc} - V_{CE(sat)} = I_{B2}R_E + I_{C2}(R_{thc} + R_E) \quad \text{------------------3.12}$$

Solving Eqs. (3.11) and (3.12), we get I_{B2} and I_{C2}:

$$I_{B2(min)} = \frac{I_{C2}}{h_{FE}}$$

If $I_{B2} >> I_{B2(min)}$, Q_2 is in saturation,

Therefore, the stable-state voltages and currents are

$$V_{EN} = V_{EN2} = (I_{B2} + I_{C2})R_E \quad \text{------------------ 3.13}$$

$$V_{CN2} = V_{EN2} + V_{CE(sat)} \quad \text{------------------ 3.14}$$

$$V_{BN2} = V_{EN2} + V_\sigma \quad \text{------------------ 3.15}$$

$$V_{BN1} = V_{CN2} \times \frac{R_2}{R_1 + R_2} \quad \text{------------------3.16}$$

$$V_{BE1} = V_{BN1} - V_{EN2} \quad \text{------------------3.17}$$

If this voltage reverse-biases the emitter diode, Q_1 is OFF.

$$I_1 = \frac{V_{CC} - V_{BN2}}{R_C + R_1} \quad \text{------------------3.18}$$

$$V_{CN1} = V_{CC} - I_1 R_C \quad \text{------------------3.19}$$

$V_{CE1} = V_{CN1} - V_{EN2}$ --- 3.20

EXAMPLE PROBLEM:

Example 3.2: Calculate the stable-state currents and voltages for the circuit of Figure 3.12(a), in which *n–p–n* silicon transistors are used. Given that $V_{BE(sat)} = 0.7$ V, $V_{CE(sat)} = 0.3$ V and $h_{FE(min)} = 50$. Take $V_{CC} = 20$ V, $R_C = 4.7$ kΩ, $R_1 = 30$ kΩ and $R_2 = 15$ kΩ, $R_E = 400$ Ω.

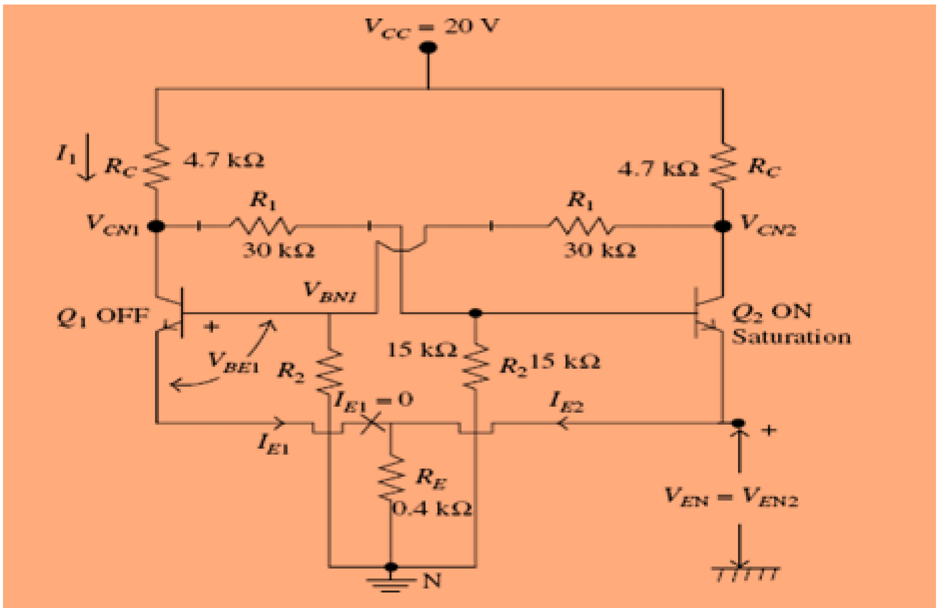

Figure 3.12 (A) A Self-Bias Bistable Multivibrator with Component Values Specified

Solution: Let Q_1 be OFF and Q_2 be ON and in saturation. To verify whether Q_2 is in saturation or not, draw the collector loop and base loop of the circuit by Thévenising at the collector and base terminals of Q_2.

$$V_{thb} = V_{CC} \times \frac{R_2}{R_C + R_1 + R_2} = 20 \times \frac{15}{4.7 + 30 + 15} = 6.03\,\text{V}$$

and

$$R_{thb} = R_2 \,||\, (R_C + R_1) = \frac{R_2(R_C + R_1)}{R_2 + R_C + R_1} = \frac{(15)(30 + 4.7)}{4.7 + 30 + 15} = 10.47\,\text{k}\Omega$$

$$V_{thc} = V_{CC} \times \frac{(R_1 + R_2)}{R_C + R_1 + R_2} = \frac{20 \times (30 + 15)}{4.7 + 30 + 15} = 18.10\,\text{V}$$

$$R_{thc} = (R_1 + R_2) \,||\, R_C = \frac{(30 + 15)(4.7)}{30 + 15 + 4.7} = 4.25\,\text{k}\Omega$$

The base and collector loops of Q_2 are drawn as shown in Figure 3.12 (b).

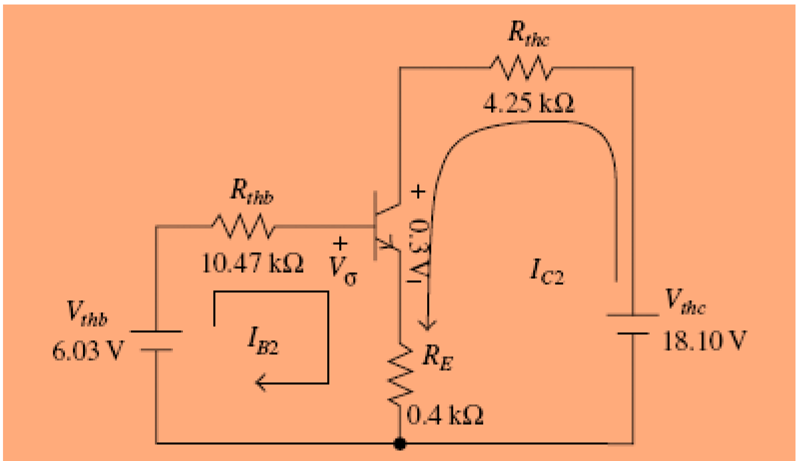

Figure 3.12 (B) The Circuit to Calculate the Base and Collector Currents

- Writing the KVL equations of the input and output loops:
- $6.03 - 0.7 = (10.47 + 0.4)\ I_{B2} + 0.4\ I_{C2}$
- $18.10 - 0.3 = 0.4\ I_{B2} + (4.25 + 0.4)\ I_{C2}$
- That is,
- $5.33\text{ V} = 10.87\, I_{B2} + 0.4\, I_{C2}$
- $17.80\text{ V} = 0.4\, I_{B2} + 4.65\, I_{C2}$
- Solving these equations, we get
- $I_{B2} = 0.35$ mA $\quad I_{C2} = 3.79$ mA

$$I_{B2\min} = \frac{I_{C2}}{h_{FE}} = \frac{3.79\text{ mA}}{50} = 0.075\text{ mA}$$

$$I_{B2} \gg I_{B2(\min)}$$

Hence, Q_2 is saturation.

- $V_{EN} = V_{EN2} = (I_{B2} + I_{C2})\ R_E$ => $V_{EN2} = (0.35 + 3.79)\ (0.4) = 1.656$ V
- $V_{CN2} = V_{EN2} + V_{CE(sat)} = (1.656\text{ V} + 0.3\text{ V}) = 1.956$ V
- $V_{BN2} = V_{EN2} + V_{BE(sat)} = (1.656\text{ V} + 0.7\text{ V}) = 2.356$ V
- $V_{BN1} = V_{CN2} \times \dfrac{R_2}{R_1 + R_2} = \dfrac{1.956 \times 15}{15 + 30} = 0.652\text{ V}$
- $V_{BE1} = V_{BN1} - V_{EN2} = (0.652\text{ V} - 1.656) = -1.004$ V
- As this voltage reverse-biases the emitter diode, Q_1 is OFF.
- $I_1 = \dfrac{V_{CC} - V_{BN2}}{R_C + R_1} = \dfrac{20 - 2.356}{4.7 + 30} = 0.508\text{ mA}$
- $V_{CN1} = V_{CC} - I_1 R_C = 20 - (0.508)\ (4.7) = 17.61$ V
- The stable-state voltages are: V_{CN1} =17.61V, V_{BN1} =0.652V, V_{CN2} =1.956V,

➧ V_{BN2} = 2.356 V, V_{EN} = 1.656 V

3.3.3 Commutating Capacitors:

In the initial stable state $\boldsymbol{Q}_2$ is ON and in saturation, $\boldsymbol{Q}_1$ is OFF. Once a trigger is applied [see Figure 3.13] to change the state of the devices in the bistable multivibrator, because of the stray capacitances of the devices they may not go into the next state immediately. This is a problem which needs to be overcome.

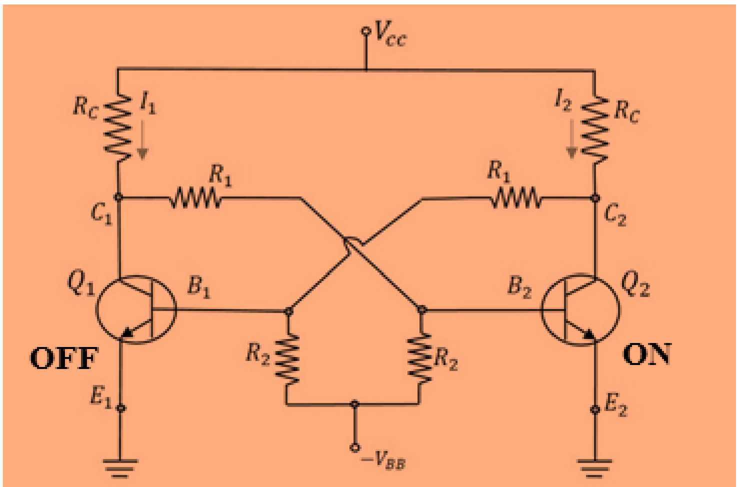

Figure3.13 A Fixed Bias Bistable Multivibrator

Now, let a negative pulse be applied at the base $\boldsymbol{Q}_2$ to drive it into the OFF state and consequently $\boldsymbol{Q}_1$ into the ON state. Prior to the application of this trigger the voltage at the second collector was $\boldsymbol{V}_{\boldsymbol{CE}(\mathrm{sat})}$. On the application of a trigger at

$\boldsymbol{t}$ = 0, as $\boldsymbol{Q}_2$ goes into the OFF state, the voltage at its collector rises from $\boldsymbol{V}_{\boldsymbol{CE}(\mathrm{sat})}$ to $\boldsymbol{V}_{\boldsymbol{CC}}$. Let the change in voltage at the second collect be $\Delta \boldsymbol{v}_{\boldsymbol{C}}$, a step voltage. That is,

$$\Delta \boldsymbol{vC} = V_{CC} - V_{CE(sat)} \text{ --3.21}$$

This voltage change at the second collector is coupled to the first base through $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$, as shown in Figure 3.14 (a). As a result, $\boldsymbol{Q}_1$ is expected to switch into the ON state. If the attenuator is a simple resistive attenuator as seen in Figure 3.14 (a), the moment $\boldsymbol{Q}_2$ switches into the OFF state, $\boldsymbol{Q}_1$ quickly switches into the ON state. However, between the input terminals of $\boldsymbol{Q}_1$ if a stray capacitance $\boldsymbol{C}_{\boldsymbol{i}}$ is present, then the attenuator circuit in Figure 3.14 (a) gets modified as shown in Figure 3.14 (b).

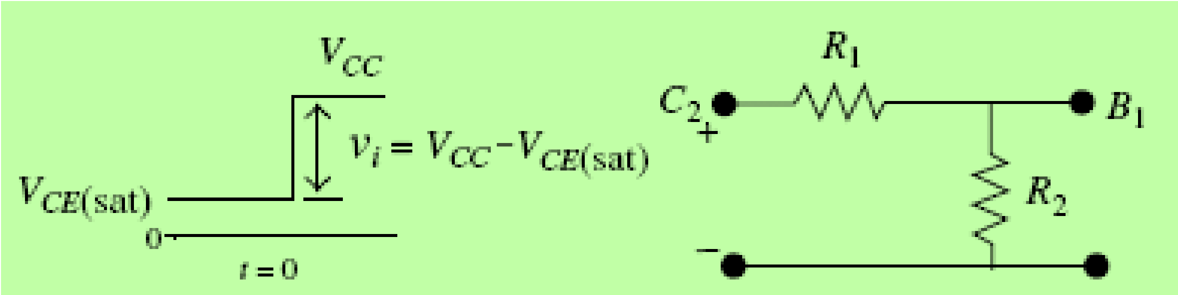

Figure 3.14 (A) A Simple Resistive Attenuator

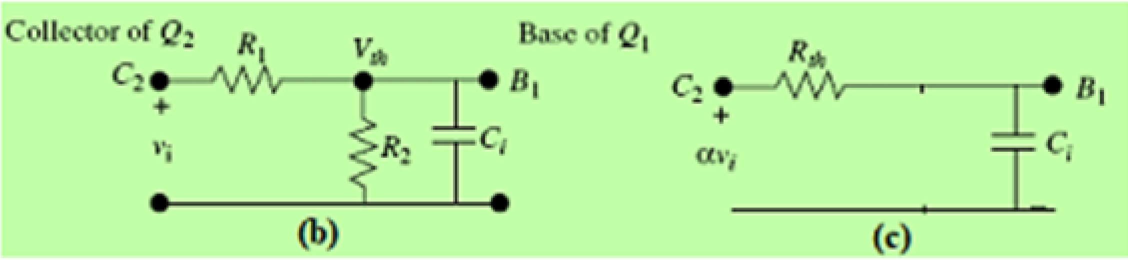

Figure 3.14(b) An attenuator considering the stray capacitance , (c) An attenuator circuit with Thevenin source and its internal resistance

To reduce this two-loop network into a single loop network, let us Thévenise the circuit.

$$V_{th} = v_i \frac{R_2}{R_1 + R_2} = \alpha V_i \quad \text{------------------------------------- 3.22}$$

Where

$$\alpha = \frac{R_2}{R_1 + R_2} \quad \text{---------------------------------------3.23}$$

and

$$R_{th} = R_1 || R_2 \quad \text{---------------------------------------3.24}$$

Then the circuit shown in Figure 3.14 (b) reduces to that shown in Figure 3.14 (c). Now, only when the voltage at $\boldsymbol{B}_1$ rises to 90 per cent of its final value, the device $\boldsymbol{Q}_1$ is assumed to switch from the OFF state into the ON state. This time interval is the rise-time of the circuit.

$$t_r = 2.2\, R_{th} C_i \quad \text{---3.25}$$

As an example, if $\boldsymbol{R}_1 = \boldsymbol{R}_2 = 1$ MΩ, $\boldsymbol{R}_{th} = 0.5$ MΩ and if $\boldsymbol{C}_i = 10$ nF then:

$$\boldsymbol{t}_r = 2.2 \times 0.5 \times 10^6 \times 10 \times 10^{-9} = 11 \text{ ms}$$

Having applied a trigger at $\boldsymbol{t} = 0$ so as to switch $\boldsymbol{Q}_2$ into the OFF state and consequently $\boldsymbol{Q}_1$ into the ON state, it is understood that $\boldsymbol{Q}_1$ will not go into the ON state unless a time period of 11ms elapses from the instant the trigger is applied, which is a large time delay and is not acceptable. Such an attenuator is called uncompensated attenuator. From the above discussion, it is evident that conduction is transferred from Q_2 to Q_1 after a finite time interval (11ms) from the instant the trigger is applied. This time delay is called the transition time. Transition time is, therefore, defined as the time taken for conduction to be transferred from one device to the other. This means that transition time is the time interval from the instant the trigger is applied at the base of Q_2 which is ON to the instant when Q_1 switches ON. To reduce this transition time condenser C_1 is connected in shunt with resistor R_1, as shown in Figure 3.14 (d).

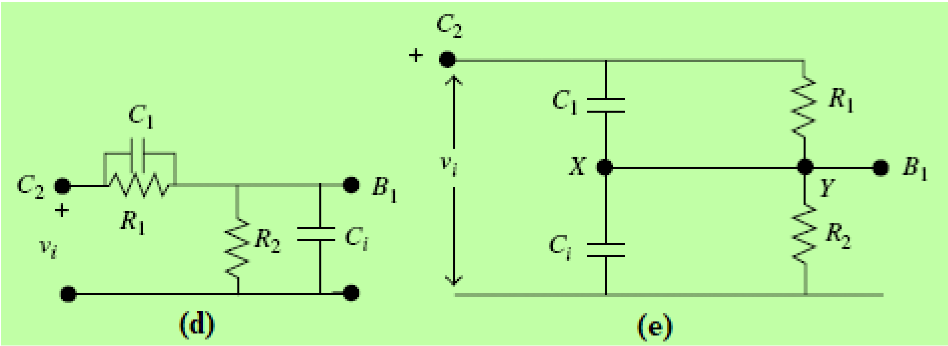

Figure 3.14 (d) An attenuator circuit with condenser C_1 in shunt with resistor R_1, (e)The redrawn circuit of Figure 3.14 (d)

Then the attenuator circuit shown in Figure 3.14 (d) is redrawn as shown in Figure 3.14 (e). The circuit shown in Figure 3.14 (e) is in the form of a bridge comprising of four arms R_1, C_1, R_2 and C_i. The bridge is said to be balanced when $R_1C_1 = R_2C_i$. If this condition is satisfied, then the current in the loop XY is zero and it appears as though there is no physical connection between X and Y, as shown in Figure 3.14 (e). As the capacitor C_1 is connected in shunt with resistor R_1 it helps in reducing the transition time, this capacitor is called the speed-up capacitor, commutating capacitor or transpose capacitor. The collector-coupled bistable multivibrator using commutating capacitor is shown in Figure 3.15.

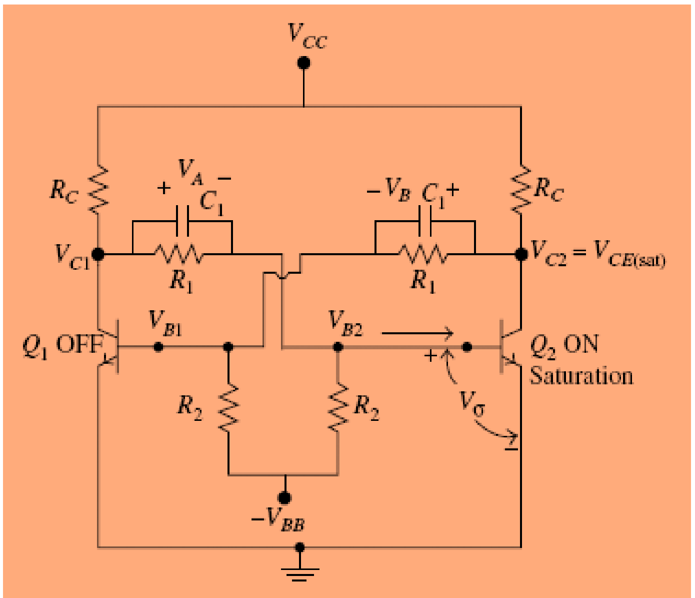

Figure 3.15 A fixed bias multivibrator with Commutating Capacitors

It is clear that a commutating condenser is connected across $\boldsymbol{R}_1$ to reduce the transition time. So therefore, in a bistable multivibrator there are two cross-coupling resistances $\boldsymbol{R}_1$ and $\boldsymbol{R}_1$, $\boldsymbol{C}_1$ and $\boldsymbol{C}_1$ need to be connected across these resistances to transfer conduction from one device to the other, soon after the application of the trigger.

However, the moment the commutating capacitor are connected to reduce the transition time, voltages of value V_A and V_B exist across the two capacitors. When Q_1 is OFF and Q_2 is ON, the values of these two voltages can be calculated using the following equations:

$$V_A = V_{C1} - V_{B2} = V_{CC} - V\sigma \text{ -- } 3.26$$

$$V_B = V_{C2} - V_{B2} = V_{CE(sat)} - V_{B1}(a\ small\ negative\ voltage) \text{ ----------------- } 3.27$$

If a trigger is applied to change the state of the devices, Q_1 quickly goes into the ON state when Q_2 switches into the OFF state as the transition time is negligible. However, the voltages across the two capacitors will not switch instantaneously. The multivibrator is said to have settled down in its new state completely only when the capacitor voltages also switch. The next trigger, to once again change the state of the two devices, can be applied only then. The interval during which the capacitor voltages interchange is called the settling time. Thus, settling time is defined as the time taken for the capacitor voltages to interchange after conduction is transferred from one device to the other, on the application of a trigger.

3.3.4 THE RESOLUTION TIME AND THE MAXIMUM SWITCHING SPEED OF A BISTABLE MULTIVIBRATOR:

The sum of transition time and settling time is called the resolution time of the bistable multivibrator.

$t_{res} = t_{trans} + t_{settling} \approx \ t_{settling}, \ as \ \ t_{trans}$ is small -------------------------------------3.28

where, t_{res} is the resolution time, t_{trans} is the transition time, and $t_{settling}$ is the settling time. Thus, the resolution time is the minimum time interval required between successive trigger pulses to reliably drive the multivibrator from one state to the other. The reciprocal of the resolution time is called the maximum switching speed of a bistable multivibrator.

$f_{(max)} = \frac{1}{t_{res}}$ --3.29

Eq. (3.29) tells us as to how fast we can switch the bistable multivibrator from one stable state to the other. To be able to reliably trigger the bistable multivibrator from one stable state to the other, we have to wait for a time interval t_{res}. The transition time, as we have seen, is appreciably reduced by connecting commutating condensers. As a result, the resolution time is approximately equal to the settling time, during which period the voltages across the two commutating condensers interchange. The recharging time constants associated with the two condensers, C_1 and C_1' shown in Figure 3.15 are used to calculate the resolution time t_{res}. In order to distinguish between the two capacitors in the circuit, they are labelled differently as C_1 and C_1', though in actuality the two capacitors are equal i.e., $C_1 = C_1'$. To find the recharging time constant associated with the capacitor C_1', consider the circuit shown in Figure 3.16 (a).

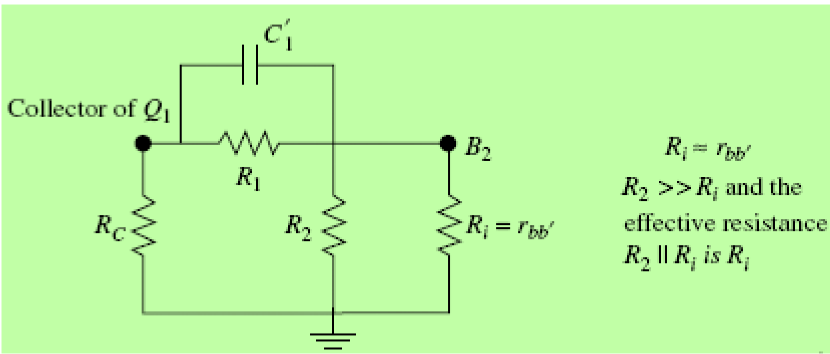

Figure 3.16 (a) The circuit to calculate the recharging time constant of capacitor C_1'

As Q_2 is ON and in saturation, $r_{bb'}$ appears between its base and emitter terminals. The net resistance in the circuit is R', as shown in Figure 3.16 (b).

$R' = R_1||(R_C + R_i) = R_1||(R_C + r_{bb'}) \approx R_1||R_C$---3.30

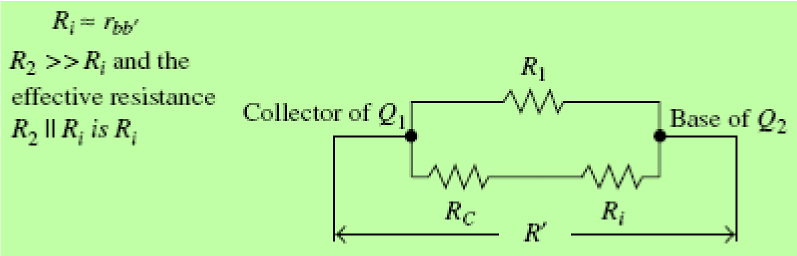

Figure 3.16 (b) The calculation of the effective resistance, R'

Hence, the recharging time constant associated with this condenser C_1' is,

$\tau' = R' C_1'$ --3.31

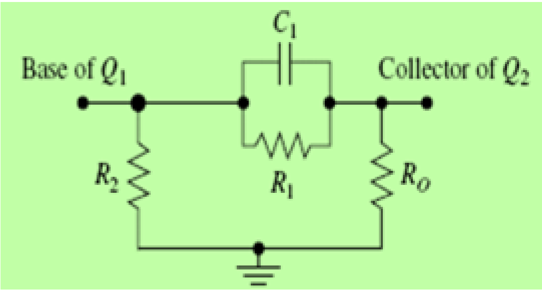

Figure 3.16 (c) The circuit to calculate the recharging time constant of C_1

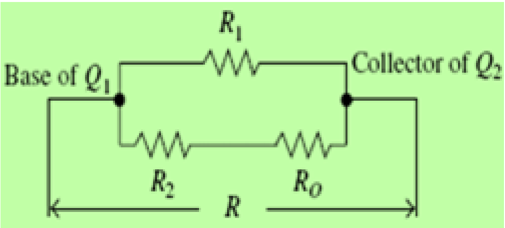

Figure 3.16 (d) The calculation of the effective resistance, R

To find the recharging time constant associated with C_1, the corresponding circuit is shown in Figure 3.16 (c). *Ro* is the output resistance of *Q2* (in saturation) taking *RC* also into account, which is small. The net resistance in the circuit is *R*, as shown in Figure 3.16 (d).

$R = R_1 \; || \; (R_2 + R_o)$

$R = R_1 \,||\, R_2 \;\; as\; R_o is\;\; small$ ---3.32

The recharging time constant associated with $C_1 = \tau$ is calculated from Figure 3.16 (e).

$\tau = R \;\; C_1$--3.33

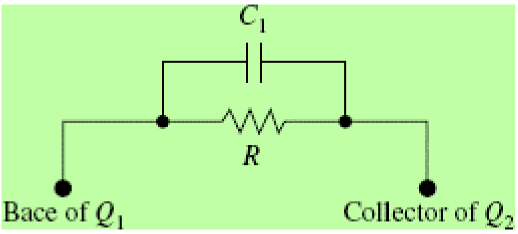

Figure 3.16 (e) The circuit to calculate τ

From Eqs. (3.31) and (3.33) it is evident that $\tau > \tau'$. After conduction is transferred from one device to the other, it is assumed that voltages across the capacitors interchange in a time period ($\tau + \tau'$). However, as $\tau > \tau'$, if the resolution time is taken to be 2τ, the voltages across these capacitors would certainly interchange before the application of the next trigger. Hence,

$t_{res} = 2\,\tau = 2 \times \frac{R_1\,R_2\,C_1}{R_1+R_2}$ --- 3.34

And the reciprocal of it is,

$f_{(max)} = \frac{R_1 + R_2}{2\,R_1\,R_2\,C_1}$ -- 3.35

3.3.5 METHODS OF IMPROVING THE RESOLUTION TIME OF A BISTABLE MULTIVIBRATOR:

The resolution time, as given by Eq. (3.34), is $t_{res} = 2C_1\,(R_1\,//R_2)$. For reducing the resolution time and hence, improving the switching speed, the following considerations have to be taken into account:

1. A finite transition time exists mainly because of stray capacitances of the transistor. Commutating condensers are used, to reduce the transition time, and once they are used there is a settling time. If devices with negligible stray

capacitances are used, the problem of settling time does not arise at all. Similarly, to reduce the resolution time the devices with negligible stray capacitances called as switching devices are chosen.

2. However, for the devices chosen, if the influence of stray capacitances cannot be neglected, then invariably commutating condensers (C_1 and C_1') need to be used. For t_{res} to be small, C_1 (= C_1') must be small. Though, if C_1 is smaller, transition time is lengthened. Alternately, if C_1 is larger, settling time is lengthened. For perfect compensation, C_1 is chosen as satisfying the requirement of a compensated attenuator, and is given by $C_1 = C_i\ (R_2/\ R_1)$, where C_i is the stray input capacitance of the transistor.

3. If t_{res} is to be smaller, a third option could be to have smaller values of R_1 and R_2. However, smaller values of R_1 and R_2 will load the collector of the OFF device, resulting in a reduced voltage at its collector. It is possible that this reduced voltage may not be able to drive the ON device into saturation, as desired. Secondly, smaller values of R_1 and R_2 tend to draw larger current from the dc sources, thereby, increasing the drain on the batteries.

4. For t_{res} is to be smaller, it is required to reduce switching time of the capacitors by not allowing them to go into saturation.

3.3.6 METHODS OF TRIGGERING A BISTABLE MULTIVIBRATOR:

To switch the bistable multivibrator from one stable state to the other, a trigger of proper polarity and magnitude is applied at an appropriate point in the circuit. The purpose of a trigger is to change the state of the devices. The trigger can be a dc trigger or a pulse trigger. Here, the focus is on pulse triggering only. There are two methods of triggering a bistable multivibrator using pulses: Unsymmetrical triggering and Symmetrical triggering.

(a) Unsymmetrical Triggering: In this method of triggering, one trigger pulse, taken from a source, is applied at one point in the circuit. The next trigger pulse taken from a different source is applied at a different point in the circuit [see Figure 3.17 (a)]. It has been mentioned earlier that the trigger is applied at the base of the ON device. However, since commutating condensers are connected in this circuit, the trigger pulse is not connected to the base of Q_2 directly, but is applied at the collector of Q_1 through a condenser. As the capacitor behaves as a short circuit when there is a sudden change in voltage, the negative pulse applied at the collector of Q_1 is coupled to the base of Q_2.

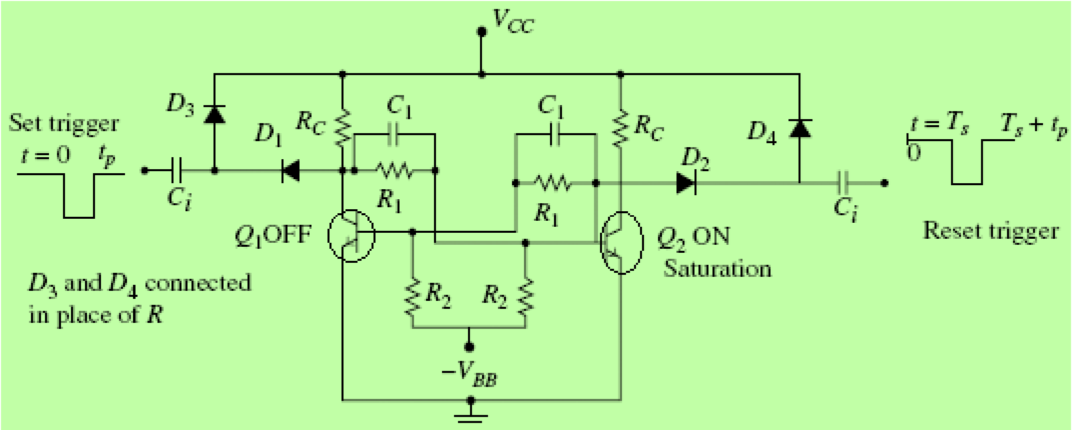

Figure 3.17 (a) The Unsymmetrical Triggering of a Bistable Multivibrator

Let the set trigger be applied to the circuit at t = 0. If Q_1 is OFF, the voltage at this collector is V_{CC}. Therefore, D_1 is ON and this negative pulse appears at the base of Q_2 as the first collector and the second base are connected through C_1. Q_2 goes into the OFF state and Q_1 into the ON state. The next trigger pulse, i.e., the reset pulse, is applied through D_2 at the second collector which is coupled to the first base through C_1. Q_1 now goes into the OFF state and Q_2 into the ON state. Let us look at the voltages at the two collectors as shown in Figure 3.17 (b).

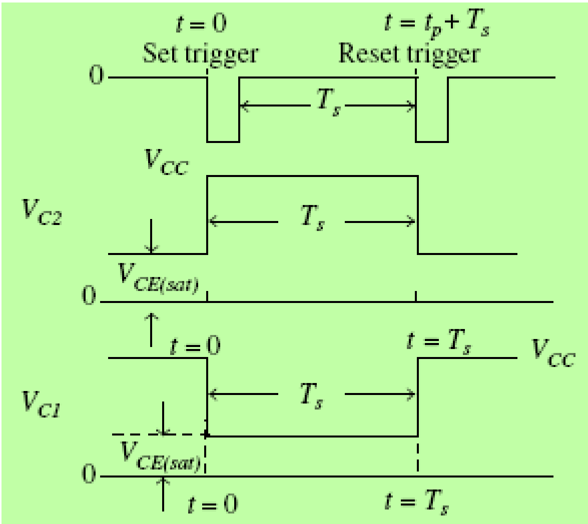

Figure 3.17 (b) the voltages at the two collectors on the application of trigger pulses

The set trigger pulse applied at t = 0 sets the voltage at the second collector to V_{CC}. The reset pulse applied after a time interval T_s, resets the voltage at the second collector to $V_{CE(\text{sat})}$. Hence, a pulse is generated at this collector and similarly at the first collector. The duration of this pulse is equal to the spacing between successive trigger pulses. Hence, unsymmetrical triggering is used to generate a gated output, the width of this gate being the spacing between two successive triggers. The diodes D_3 and D_4 are used in place of a resistance R. When a negative trigger pulse appears, the diode is OFF (D_3 or D_4); the large reverse resistance of the diode avoids loading the trigger source. When the trigger is absent, the diode is ON and offers a negligible resistance so that the charge on the capacitor C_i can be quickly removed.

(b) Symmetrical Triggering: In symmetrical triggering, successive trigger pulses taken from the same source and applied at the same point in the circuit will cause the multivibrator to change from one stable state to the other. This method of triggering is normally used in counters, as shown in Figure 3.18 (a).

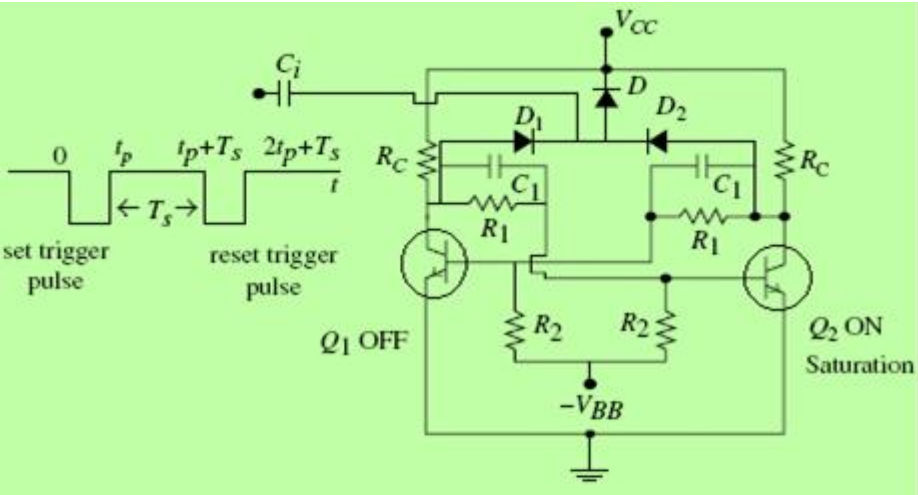

Figure 3.18 (a) The symmetrical triggering of a Bistable Multivibrator

In the circuit shown in Figure 3.18 (a) the purpose of D is similar to the diodes D_3 and D_4 used in Figure 3.17 (a).The first trigger pulse (Set pulse) makes D_1 conduct and this pulse is coupled to the base of Q_2 and drives Q_2 into the OFF state and Q_1 into the ON state. The next trigger pulse (Reset pulse) applied at $t = t_1$ is coupled to the first base as D_2 is now ON. Hence, Q_1 again goes into the OFF state and Q_2 into the ON state. D_1 and D_2 are called steering diodes as these diodes steer the trigger to the appropriate base.

A bistable multivibrator is represented by a block having a trigger input and the outputs at collectors of Q_1 and Q_2, as shown in Figure 3.18 (b).

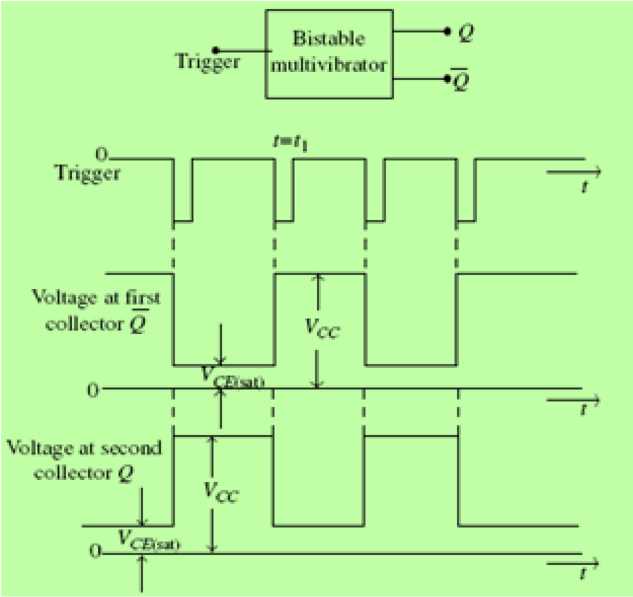

Figure 3.18 (b) The trigger and outputs with symmetrical triggering of a Bistable Multivibrator

From the above waveforms, it is seen that for every two trigger pulses, there is one pulse at Q. Hence, a bistable multivibrator is also called a scale-of-two-circuit.

3.4 SCHMITT TRIGGER:

An emitter-coupled Bistable Multivibrator is also called a Schmitt trigger, named after the designer of the vacuum tube version. In addition to being used as a bistable multivibrator, it has some more important applications. In the Schmitt trigger circuit shown in Figure 3.19, it is seen that the output of the first transistor is connected to the input of the second transistor through a potential divider network comprising R_1 and R_2. This is simply an attenuator circuit. Normally R_1 and R_2 are reasonably large resistors so as to avoid loading the collector of Q_1. Further, the emitter resistance R_E stabilizes the currents and voltages. Note that the second collector and the first emitter are not involved in the regenerative loop (there is no cross-coupling from the second collector to the first base). So, when used as a bistable multivibrator, there is no loading on the second collector and the trigger is applied at the first base and the output is taken from the second collector.

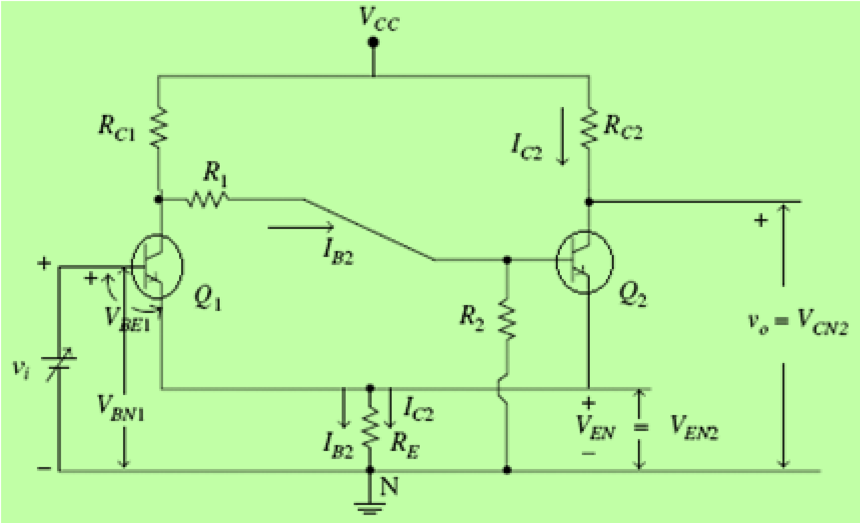

Figure 3.19 The Schmitt trigger

As long as the battery voltage *vi* is small, Q_1 is OFF. The voltage at this collector is approximately V_{CC}. This voltage is coupled to the second base through R_1 and R_2. As a result, Q_2 can conduct. If Q_2 conducts, it can operate in the active region or it may be driven into saturation.

Let it be assumed that Q_2 is in the active region. The base current I_{B2} and collector current I_{C2} flows through R_E. Therefore, a voltage $V_{EN} = V_{EN2}$ is developed in R_E. As $V_{BE1} = V_{BN1} - V_{EN2}$ and if V_{BE1} reverse-biases the emitter diode of Q_1, then as assumed Q_1 is OFF. If $\boldsymbol{V_{BN1}}$ ($\boldsymbol{v_i}$) is increased, at a value ($\boldsymbol{V_{EN2}} + \boldsymbol{V_{\gamma 1}}$), $\boldsymbol{Q_1}$ begins to conduct. As a result, the voltage at the second base decreases, hence the base current of $\boldsymbol{Q_2}$ decreases, its collector current also reduces and consequently the voltage at the second collector rises. If the input is increased further, $\boldsymbol{Q_1}$ goes into the ON state and $\boldsymbol{Q_2}$ into the OFF state. If the loop gain is less than unity (this condition can be satisfied by reducing the collector load of $\boldsymbol{Q_1}$), there exists a region of linearity in the transfer characteristic. In this region an incremental change at the input $\Delta\boldsymbol{v_i}$ will cause a proportional change in the output, $\Delta\boldsymbol{v_o}$ as shown in Figure 3.20 (a). If the loop gain is made equal to 1 by adjusting $\boldsymbol{R_{C1}}$ and $\boldsymbol{R_{C2}}$, the transfer characteristic is as shown in Figure 3.20 (b). If on the other hand, the loop gain is made greater than 1, the transfer characteristic is an S-shaped characteristic, as shown in Figure 3.20 (c).

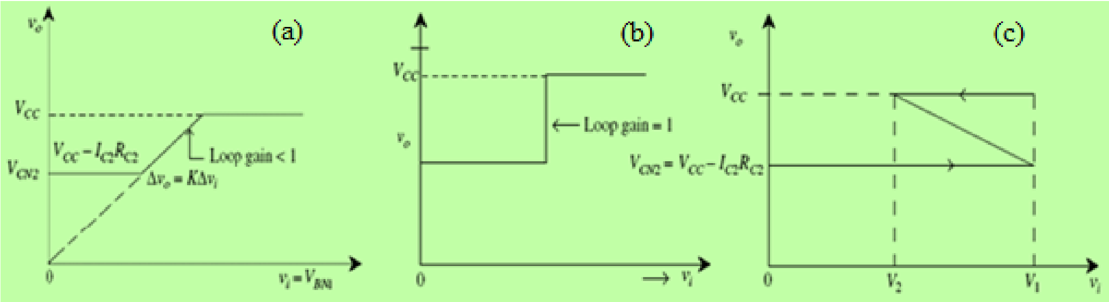

Figure 3.20 (a) The transfer characteristic of a Schmitt trigger when the loop gain < 1, (b) The transfer characteristic of a Schmitt trigger when the loop gain is 1, (c) The transfer characteristic of a Schmitt trigger when the loop gain > 1.

When the input is increased from 0 to a larger value, at a voltage V_1, the output suddenly jumps from a smaller value to V_{CC} as shown in Figure 3.21 (a). Even if the input is increased further, the output remains at V_{CC}. If on the other hand, the input is decreased, then at a voltage V_2 the output falls from V_{CC} to a smaller value, as shown in Figure 3.21 (b). If these two curves are combined together, the resultant transfer characteristic, that gives the relation between the input and the output, is shown in Figure 3.21 (c).

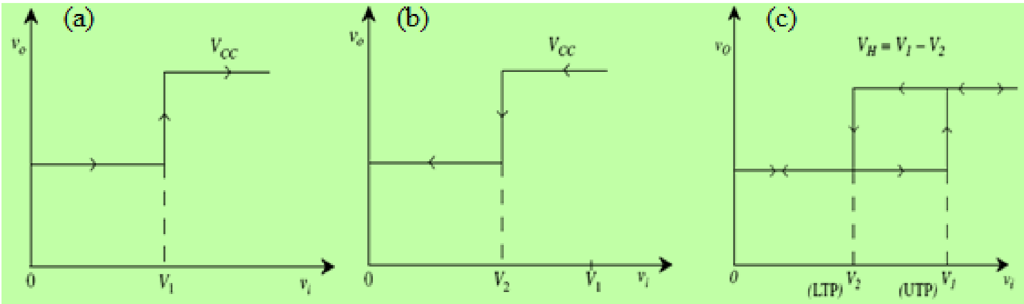

Figure 3.21 (a) The output rises suddenly to V_{CC}, (b) When the input is decreased the output falls from V_{CC}, (c) The transfer characteristics of a Schmitt trigger.

V_1 is called the upper triggering point (UTP) and V_2 is called the lower triggering point (LTP). The closed loop in Figure 3.21 (c) is termed the hysteresis loop and the difference in voltages V_1 and V_2 is called the hysteresis voltage, V_H. Thus, $V_H = V_1 - V_2$. It is seen from the above discussion that a Schmitt trigger exhibits hysteresis, i.e., when the input v_i is increased to reach a voltage V_1 it is required to first pass through a point, V_2 at which the reverse transition takes place. Similarly, when the input now is reduced to reach V_2 it has to pass through the point V_1. This is called hysteresis. This characteristic of the Schmitt trigger is used to an advantage in wave shaping applications.

3.4.1 Calculation of the Upper triggering Point ($V1$):

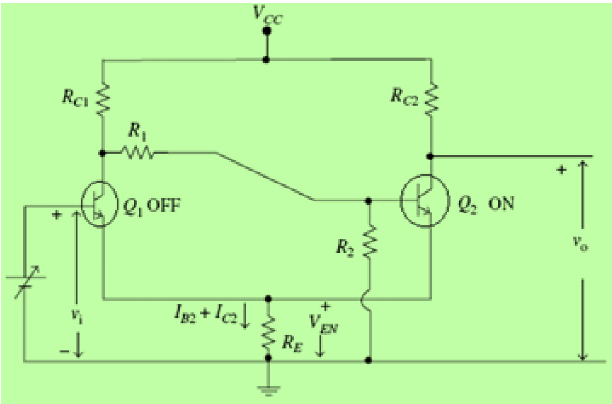

Figure 3.22 (a) Schmitt trigger circuit

Consider the Schmitt trigger circuit, shown in Figure 3.22(a), when the input is increased, till $\boldsymbol{V}_1$ is reached $\boldsymbol{Q}_1$ is OFF and $\boldsymbol{Q}_2$ is ON. As a result, $\boldsymbol{I}_{B2}$ and $\boldsymbol{I}_{C2}$ flow through $\boldsymbol{R_E}$ developing a voltage $\boldsymbol{V_{EN}}$ in $\boldsymbol{R_E}$. Now, if the input is such that its value is ($\boldsymbol{V_{EN}}$ + $\boldsymbol{V}_{\gamma1}$) = $\boldsymbol{V}_1$(UTP), $\boldsymbol{Q}_1$ switches into the ON state and $\boldsymbol{Q}_2$ switches into the OFF state.

If the circuit show in Figure 3.22(a) is Thévenised at the base of $\boldsymbol{Q}_2$, the Thévenin voltage source is,

$V^{|} = V_{CC} \times \frac{R_2}{R_{C1}+R_1+R_2}$ ---3.36

and its internal resistance R' is given by the relation:

$R^{|} = R_2||(R_{C1} + R_1)$ --3.37

The resultant simplified circuit is shown in Figure 3.22 (b).

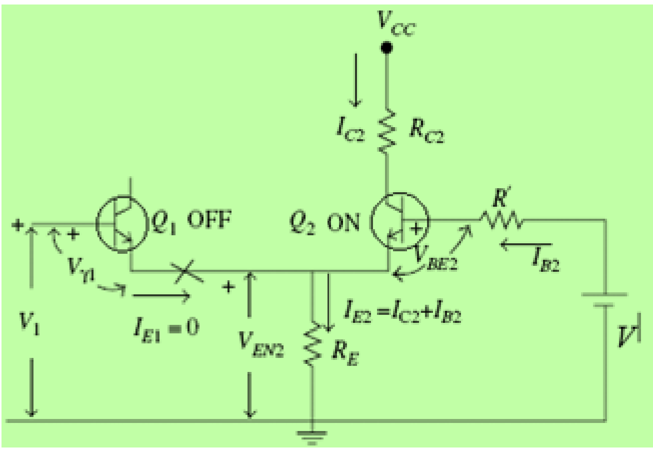

Figure 3.22 (b) The circuit that enables computation of V₁

$$I_{E2} = I_{B2} + I_{C2} = I_{B2}\left(1 + \frac{I_{C2}}{I_{B2}}\right) = I_{B2}(1 + h_{FE})$$ --3.38

The total current in $\boldsymbol{R_E}$ is $\boldsymbol{I_{B2}}$ (1 + $\boldsymbol{h_{FE}}$) and the current in $\boldsymbol{R'}$ is $\boldsymbol{I_{B2}}$. As far as $\boldsymbol{I_{B2}}$ is concerned, $\boldsymbol{R_E}$ is seen to have increased by a factor (1 + $\boldsymbol{h_{FE}}$). The net voltage in the base loop is, ($\boldsymbol{V'} - \boldsymbol{V_{BE2}}$) and is equal to the sum of the voltage drops across $\boldsymbol{R'}$ and (1 + $\boldsymbol{h_{FE}}$) $\boldsymbol{R_E}$, as shown in Figure 3.22 (c).

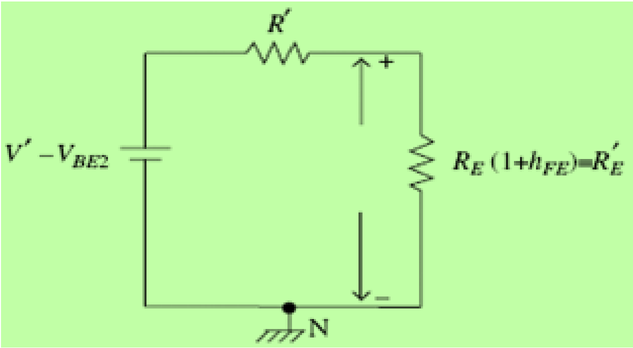

Figure 3.22 (c) The circuit to calculate V_{EN2}

$$\therefore\ V_{EN2} = \left(V' - V_{BE2}\right)\frac{R'_E}{R' + R'_E}$$

$$= \left(V' - V_{BE2}\right)\frac{R_E(1+h_{FE})}{R'+R_E(1+h_{FE})}$$ --3.39

In Eq. (3.39), as:

$R' << R_E(1 + h_{FE}) \Rightarrow R' + R_E(1 + h_{FE}) \cong R_E(1 + h_{FE})$

Then Eq. (3.39) reduces to:

$$\therefore\ V_{EN2} = \left(V' - V_{BE2}\right)\frac{R_E\,(1+h_{FE})}{R_E\,(1+h_{FE})}$$ --3.40

$$= \left(V' - V_{BE2}\right)$$ ---3.41

From Figure 3.22 (b), using Eq. (3.41):

$$V_1 = V_{EN2} + V_{\gamma 1}$$ ---3.42

The calculation of V_1 is made based on the assumption that Q_2 is in the active region. Now, to verify whether Q_2 is in the active region, V_{CB2} is calculated and checked if this reverse-biases the collector diode by a reasonable voltage or not. If it does, the device Q_2 is indeed in the active region.

From the circuit in Figure 3.22 (b), we have:

$$V_{CB2} = V_{CE2} - V_{BE2} \quad \text{and} \quad V_{CE2} = V_{CC} - I_{C2}R_{C2} - V_{EN2}$$

$$\therefore \; V_{CB2} = V_{CC} - I_{C2}R_{C2} - V_{EN2} - V_{BE2} \qquad \text{--3.43}$$

To calculate V_{CB2} using Eq. (3.43), we have to find I_{C2}.

$$V_{EN2} = (I_{B2} + I_{C2})R_E = I_{C2}\left(1 + \frac{1}{h_{FE}}\right)R_E$$

$$V_{EN2} = I_{C2}R_E^{||} \qquad \text{--3.44}$$

Where,

$$R_E^{||} = \left(1 + \frac{1}{h_{FE}}\right)R_E \text{--3.45}$$

Substituting Eq. (3.44) in Eq. (3.42) we get:

$$V_1 = I_{C2}R_E^{||} + V_{\gamma 1} \text{---3.46}$$

where $R_E^{||}$ is given by Eq. (3.45). From Eq. (3.44) I_{C2} is given as:

$$I_{C2} = \frac{V_{EN2}}{R_E^{||}} \qquad \text{--3.47}$$

These calculations were made based on the assumption that $\boldsymbol{Q}_2$ is in the active region. Having made the calculations, we once again verify whether $\boldsymbol{Q}_2$ is really in the active region or not, to justify the validity of the calculations made. $\boldsymbol{V}_{CB2}$ is calculated using Eq. (3.43). If the base-collector diode is reverse-biased, then $\boldsymbol{Q}_2$ is in the active region as assumed.

3.4.2 Calculation of the Lower Trip Point (V_2):

At the voltage $\boldsymbol{V}_1$ (UTP), $\boldsymbol{Q}_1$ is ON and $\boldsymbol{Q}_2$ is OFF. Now if the input is reduced, till voltage $\boldsymbol{V}_2$ is reached, $\boldsymbol{Q}_1$ is ON and $\boldsymbol{Q}_2$ is still OFF. However, when the voltage at the input is V_2 then the voltage at the second base is $V_{EN1} + V_{\gamma 2}$. Q_2 again switches into the ON state and Q_1 into the OFF state.

Consider the Schmitt trigger circuit shown in Figure 3.22(a). The Thévenin voltage source at the first collector is:

$$V_t = V_{CC}\frac{R_1+R_2}{R_{C1}+R_1+R_2} \quad \text{---3.48}$$

and its internal resistance R_t is,

$$R_t = R_{C1}||(R_1 + R_2) \quad \text{---3.49}$$

The first collector and the second base are connected through R_1 and R_2, as shown in Figure 3.22(d).

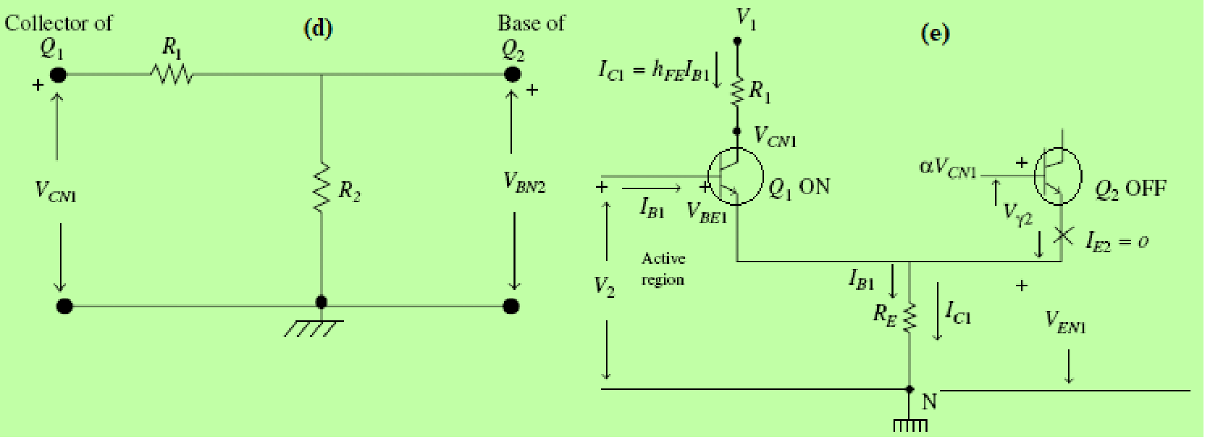

Figure 3.22(d) The coupling network from the first collector to the second base, (e) The circuit to calculate V_2

$$\therefore \; V_{BN2} = V_{CN1}\frac{R_2}{(R_1+R_2)} = \alpha\, V_{CN1} \quad \text{---3.50}$$

Where

$$\alpha = \frac{R_2}{(R_1+R_2)} \quad \text{---3.51}$$

$$R_t = \frac{R_{C1}(R_1+R_2)}{R_{C1}+R_1+R_2} \quad \text{---3.52}$$

The circuit that enables us to calculate V_2 is shown in Figure 3.22(e).

Writing the KVL equation for the base loop of Q_2:

$\alpha V_{CN1} = V_{\gamma 2} + (I_{B1} + I_{C1})\, R_E$ and $V_{CN1} = V_t - I_{C1}R_t$

$$\alpha\,(V_t - I_{C1}R_t) = V_{\gamma 2} + I_{C1}\left(1 + \frac{1}{h_{FE}}\right)R_E$$

Let: $R_E^{||} = \left(1 + \frac{1}{h_{FE}}\right)R_E$--3.53

$$\alpha\,(V_t - I_{C1}R_t) = V_{\gamma 2} + I_{C1}R_E^{||} \quad \Rightarrow \quad I_{C1}(\,\alpha\,R_t + R_E^{||}) = \alpha\,V_t - V_{\gamma 2}$$

$\Rightarrow \quad I_{C1} = \frac{(\alpha\,V_t - V_{\gamma 2})}{(\alpha\,R_t + R_E^{||})}$ --3.54

However, we have:

$$\alpha\,V_t = V_{CC}\frac{(R_1 + R_2)}{(R_{C1} + R_1 + R_2)} \times \left(\frac{R_2}{R_1 + R_2}\right) = V_{CC}\frac{R_2}{(R_{C1} + R_1 + R_2)} = V^{|}$$

$\alpha\,V_t = V^{|}$ --3.55

Therefore, substituting this value in Eq. (3.54), we get

$$\alpha\,(V_t - I_{C1}R_t) = V_{\gamma 2} + I_{C1}R_E^{||} \quad \Rightarrow \quad I_{C1}(\,\alpha\,R_t + R_E^{||}) = \alpha\,V_t - V_{\gamma 2}$$

$I_{C1} = \frac{(V^{|} - V_{\gamma 2})}{(\alpha\,R_t + R_E^{||})}$ --3.56

From the Figure 3.22(e), we get V_2 is given

$V_2 = V_{BE1} + I_{C1}R_E^{||}$--3.57

Using Eqs. (3.53), (3.55) and (3.56), $\boldsymbol{V_2}$ is calculated. To understand the method of calculation for $\boldsymbol{V_1}$ and $\boldsymbol{V_2}$, let us consider Example 3.3.

EXAMPLE PROBLEM:

Example 3.3: For the Schmitt trigger circuit shown in Figure 3.23(a), calculate $\boldsymbol{V_1}$ and $\boldsymbol{V_2}$.

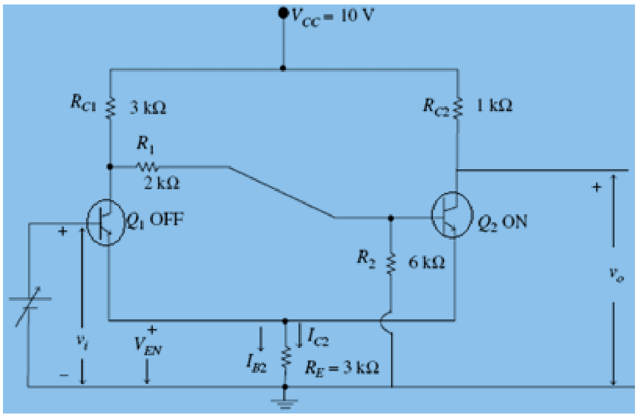

Figure 3.23(a) The Schmitt trigger with components mentioned

Solution:

a) Calculation of V_1:

Consider the Schmitt trigger circuit, shown in Figure 3.23(a). From Eq. (3.36):

$$V' = V_{CC} \times \frac{R_2}{R_{C1} + R_1 + R_2} = 10 \times \frac{6}{3+2+6} = 5.45V$$

R' the internal resistance of this Thévenin source, as given by Eq. (3.37), is:

$$R' = R_2 \mid\mid (R_{C1} + R_1) = 6 \mid\mid (3+2) = \frac{6 \times 5}{6+5} = 2.73K\Omega$$

The resultant circuit is shown in Figure 3.23(b).

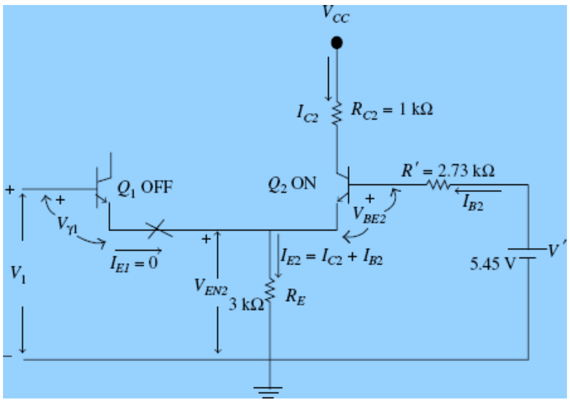

Figure 3.23(b) The circuit that enables computation of V_1

From Eq. (3.39):

$$V_{EN2} = (V' - V_{BE2}) \frac{R_E \ (1 + h_{FE})}{R' + R_E(1 + h_{FE})}$$

If Q_2 is in the active region, typically, for silicon $V_{BE2} = 0.6$ V and let $h_{FE} = 50$,

$$R_E \ (1 + h_{FE}) = 3(1+50) = 153\text{k}\Omega$$

Therefore,

$$V_{EN2} = (5.45 - 0.6) \times \frac{153}{2.73 + 153} = 4.85 \times \frac{153}{155.73} = 4.76\, V$$

Therefore,

$$V_1 = V_{EN2} + V_{BE2} = 4.76 + 0.6 = 5.36 \text{ V.}$$

The calculation of V_1 is made based on the assumption that Q_2 is in the active region. To find out whether Q_2 is in the active region or not, we calculate V_{CB2}.

$$V_{CB2} = V_{CC} - I_{C2}R_{C2} - V_{EN2} - V_{BE2}.$$

From Eq. (3.53)

$$R_E^{||} = \left(1 + \frac{1}{h_{FE}}\right) R_E = (1 + \frac{1}{50}) \times 3 = \frac{51}{50} \times 3 = 3.06 \text{ k}\,\Omega$$

$$I_{C2} = \frac{V_{EN2}}{R_E^{||}} = \frac{4.76\text{V}}{3.06 \text{ K}\Omega} = 1.56\text{mA}$$

Hence

$$V_{CB2} = 10 - (1.56 \times 1) - 4.76 - 0.6 = 10 - 6.92 = 3.08 \text{ V}$$

As the collector of $\boldsymbol{Q}_2$ is positive with respect to the base by 3.08 V the collector diode is reverse-biased. Hence, $\boldsymbol{Q}_2$ is in the active region, as assumed.

(b) Calculation of *V*2:

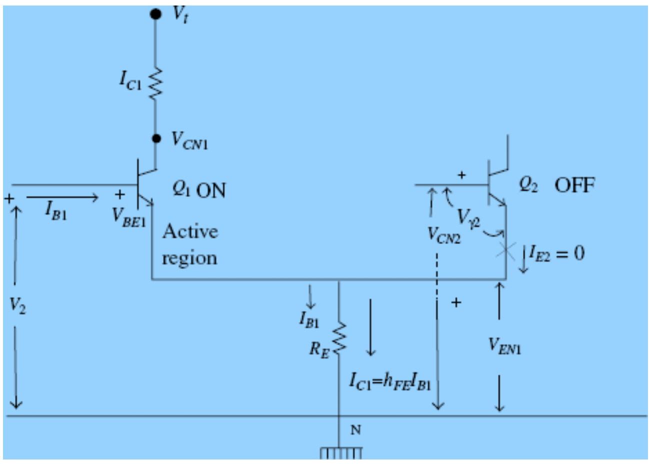

Figure 3.23(c) The circuit to calculate V_2

The circuit that enables us to calculate *V*2 is shown in Fig. 9.18(c). From the circuit values:

$$\alpha = \frac{R_2}{R_1 + R_2} = \frac{6}{2+6} = 0.75 \qquad R_t = \frac{3(2+6)}{3+2+6} = \frac{24}{11} = 2.18\,\text{k}\Omega$$

$$\alpha R_t = 0.75 \times 2.18\,\text{K} = 1.64\,\text{k}\Omega \qquad R_E'' = 3.06\,\text{k}\Omega \qquad V_2 = V_{BE1} + I_{C1} R_E''$$

$$I_{C1} = \frac{(V' - V_{\gamma 2})}{\alpha R_t + R_E''} = \frac{(5.45 - 0.5)}{1.64 + 3.06} = \frac{4.95}{4.7} = 1.05\,\text{mA}$$

$\therefore V_2 = 0.6\text{ V} + (1.05\text{ mA})\,(3.06\text{ k}\Omega) = 0.6\text{ V} + 3.22\text{ V} = 3.82\text{ V}$

Hence, for the given Schmitt trigger:

$V_1 = 5.36\text{ V} \quad V_2 = 3.82\text{ V} \quad V_H = V_1 - V_2 = 5.36 - 3.82 = 1.54\text{ V}$

3.4.3 Applications of a Schmitt Trigger:

The following are some applications of a Schmitt trigger:

(a) An emitter-coupled bistable multivibrator is called the Schmitt trigger. Hence, a Schmitt trigger can be used as a bistable multivibrator. Consider the transfer characteristic, shown in Figure 3.24(a). To use this circuit as a bistable multivibrator, the first device Q_1 is biased to have a voltage V at its base. Initially, let the output be at 0 level ($V_{CC} - I_{C2}R_{C2}$). To change this to 1(V_{CC}) apply a positive pulse at the base of Q_1, whose magnitude is more positive than ($V_1 - V$) as shown in Figure 3.24 (b). To once again change the output to a 0 level, apply a pulse at the base of $Q1$, which is negative with respect to V and whose magnitude is more negative than ($V2 - V$) as shown in Figure 3.24 (c).

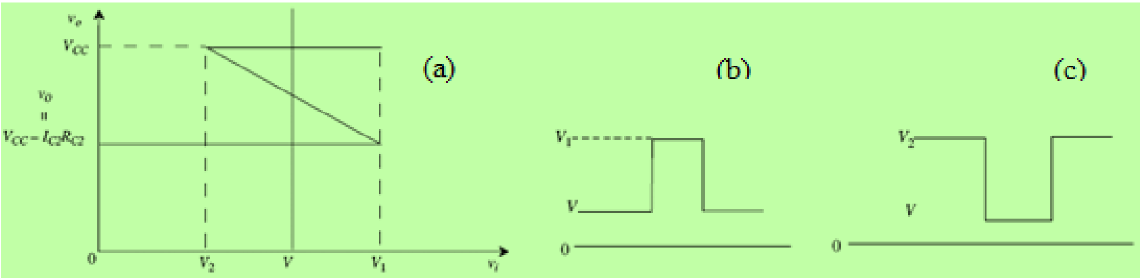

Figure 3.24 (a) The transfer characteristics of a Schmitt trigger, (b) The trigger to change the output from 0 to 1 level, (c) The trigger to change the output from 1 to 0 level

(b) A Schmitt trigger can be used as an amplitude comparator. In an amplitude comparator, the amplitude of a time varying signal is compared with a reference and it tells us the time instant at which the input has reached this set reference level. For example, consider the diode comparator circuit shown in Figure 3.25(a). As long as $v_i < V_R$, D is OFF and $v_o = v_i$. When $v_i \geq V_R$, D is ON and $v_o = V_R$.

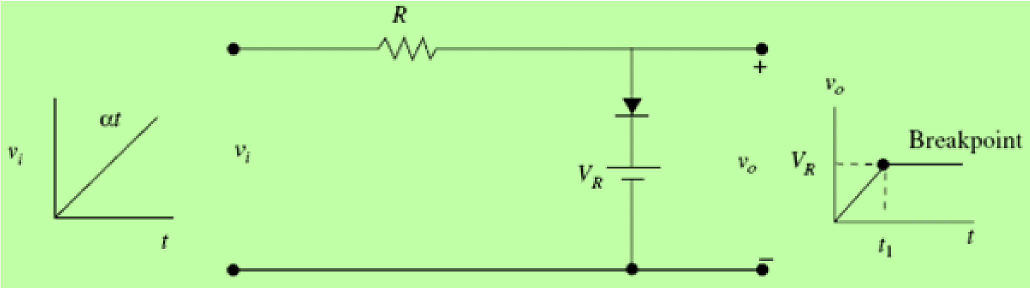

Figure 3.25(a) A diode comparator

The output follows the input till $t = t_1$ and then the slope of the output abruptly changes. This is called the break point, and t_1 is the time instant at which v_i has reached V_R.

Now consider the Schmitt trigger (in which hysteresis is eliminated) as a comparator with input and output shown in Figure 3.25(b). A relatively small dc voltage is there at the output till $\boldsymbol{V}_1(= \boldsymbol{V}_2)$ is reached at the input. The moment the input is $\boldsymbol{V}_1$, the output abruptly jumps to $\boldsymbol{V_{CC}}$. The slope of the input has no relation to the slope of the signal at the output. Thus, a Schmitt trigger can be used as a better amplitude comparator.

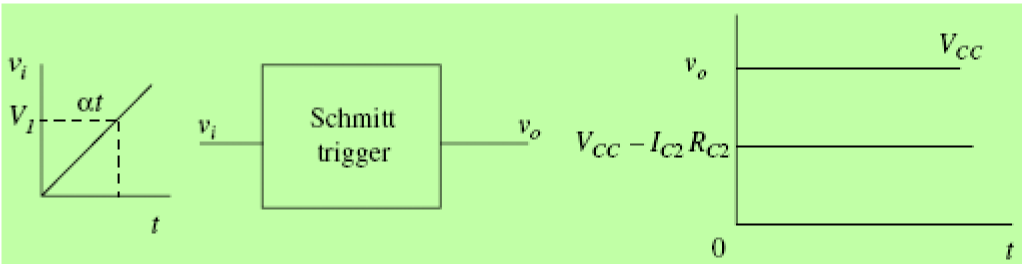

Figure 3.25(b) A Schmitt trigger as comparator

(c) A Schmitt trigger can be used as a wave shaping circuit (or a squaring circuit). It can be used to convert any arbitrarily time varying signal into a square-wave output. The only condition to be satisfied is that the input signal has amplitude more than $V1$ and also less than $V2$. Consider the input for which the output is plotted as shown in Figure 3.26.

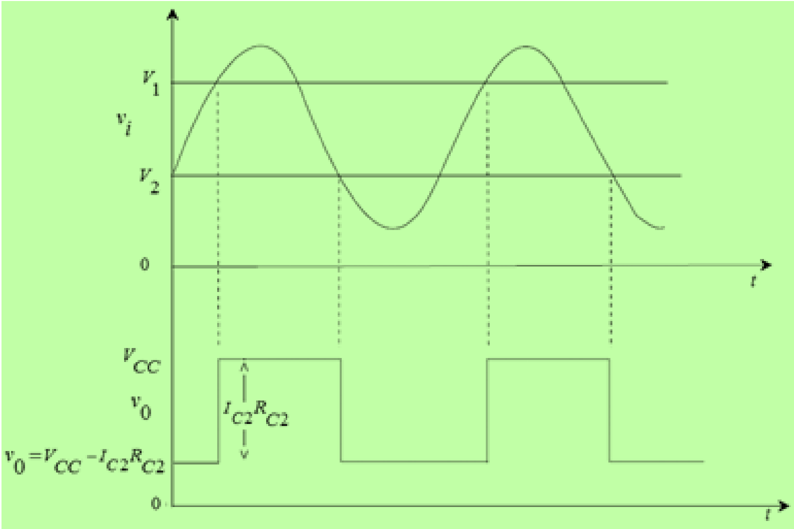

Figure 3.26 The Schmitt trigger as a squaring circuit

MONOSTABLE MULTIVIBRATORS

3.5 INTRODUCTION:

A monostable multivibrator is one in which there is a stable state and a quasi-stable state. This circuit has two devices Q_1 and Q_2, one being in the OFF state, say Q_1, and the other, Q_2, in the ON state—preferably in saturation. These devices remain in this state forever and only on the application of a trigger, the multivibrator goes into the quasi-stable state, i.e., Q_1 is ON and Q_2 is OFF. After a time interval T, the multivibrator will return to the stable state, i.e., Q_1 is OFF and Q_2 is ON. Thus, this circuit generates a pulse of duration T. Let us consider two types of monostable multivibrators:

1. Collector-coupled monostable multivibrator
2. Emitter-coupled monostable multivibrator

The output of this circuit is a pulse of time duration, T called the pulse duration, pulse width or gate width. Some other circuits can also be controlled with the help of this output for a finite time duration. Its main application is as a gate.

3.6 COLLECTOR-COUPLED MONOSTABLE MULTIVIBRATORS:

The collector-coupled monostable multivibrator is shown in Figure 3.27. Here the output from the second collector to the first base is through a resistance R_1. Hence, this circuit has one stable state and one quasi-stable state. As a negative voltage is connected to the base of the first device, it is possible that Q_1 may be OFF. In the stable state, let Q_1 be OFF and Q_2 be ON and in saturation. Therefore:

$V_{C1} = V_{CC}$,

$V_{C2} = V_{CE(\text{sat})}$,

$V_{B2} = V_{BE(\text{sat})} = V_\sigma$

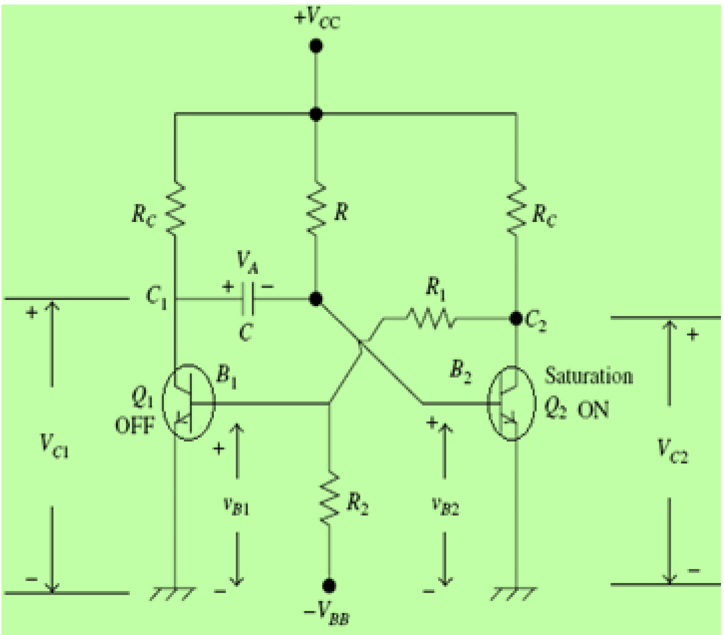

Figure 3.27 The collector-coupled monostable multivibrator

The capacitor, C now tries to charge to V_{CC} through R_C of Q_1 and a small input resistance of Q_2, as shown in Figure 3.28. As $t \rightarrow \infty$, this voltage reaches V_{CC}. To change the state of the devices, a trigger is applied at an appropriate point in the circuit.

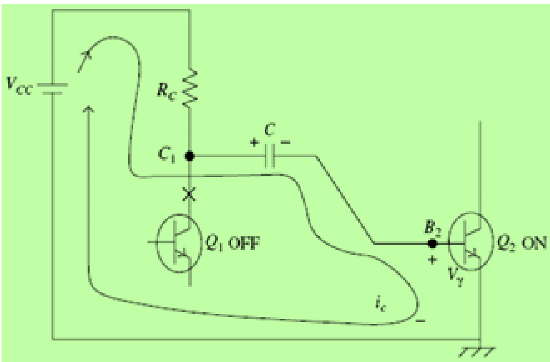

Figure 3.28 The charging of capacitor C

3.6.1 Calculation of the Time Period (T):

On the application of a trigger at $t = 0$, with a negative pulse at B_2, Q_2 goes into the OFF state and Q_1 is driven into the ON state and preferably into saturation. Hence, there is a current I_1 in Q_1. V_{C1} is $V_{CE(\text{sat})}$, if $I_1 = I_{C(\text{sat})}$, as shown in Figure 3.29(a). The charge on the capacitor $\boldsymbol{C}$ now decays with a time constant $\boldsymbol{\tau} = \boldsymbol{RC}$, as shown in Figure 3.29(b).

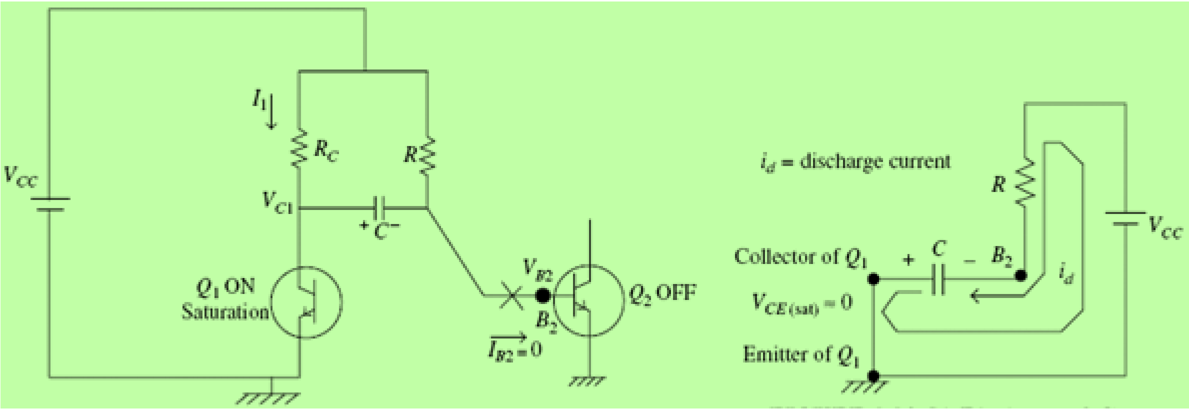

Figure 3.29 (a) When Q_1 is ON, in the quasi-stable state, (b) Discharge of C

Consequently, the voltage at $\boldsymbol{B}_2$ changes as a function of time and this voltage, $\boldsymbol{V_{B2}}$ at $\boldsymbol{B}_2$, reaches $\boldsymbol{V_\gamma}$ after a time interval $\boldsymbol{T}$. The moment the voltage at $\boldsymbol{B}_2$ is once again $\boldsymbol{V_\gamma}$, $\boldsymbol{Q}_2$ has a small base current, which in turn gives rise to collector current. Earlier the voltage at this collector was $\boldsymbol{V_{CC}}$ as $\boldsymbol{Q}_2$ was OFF. Due to this collector current, the voltage at the collector of $\boldsymbol{Q}_2$ falls, giving rise to a negative step. This negative step is coupled to the base of $\boldsymbol{Q}_1$ through $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ and thus, the base current of $\boldsymbol{Q}_1$ reduces, reducing its collector current. The voltage at the first collector now rises (earlier it was $\boldsymbol{V_{CE(\text{sat})}}$), resulting in a positive step. This change in voltage is coupled to the second base, increasing its base current further. As the collector current increases, the voltage at this collector reduces; this change in the voltage is once again coupled to the first base, reducing its base current further. Its collector current is now reduced, giving rise to a further increase in the voltage at the first collector, which once again is coupled to the second base. It is observed that regeneration takes place and $\boldsymbol{Q}_2$ is switched ON and $\boldsymbol{Q}_1$ is switched OFF, thus ending the quasi-stable state (also look at the voltage variation at $\boldsymbol{B}_2$ of $\boldsymbol{Q}_2$ shown in Figure 3.30).

As we know,

$V_{B2}(t) = v_f - (v_f - v_i)e^{-t/\tau}$ ------------ 3.56

Here, $v_f = V_{CC}$, and if Q_1 is in saturation,

$v_i = V_\sigma - I_1R_C = V_\sigma - [V_{CC} - V_{CE(\text{sat})}]$

$= V_\sigma - V_{CC} + V_{CE(\text{sat})}$

and the time constant, τ = RC

Using Eq. (3.56)

$$V_{B2}(t) = V_{CC} - [V_{CC} - V_{\sigma} + V_{CC} - V_{CE(sat)}]e^{-\frac{t}{\tau}}$$

-------------------------- ---3.57

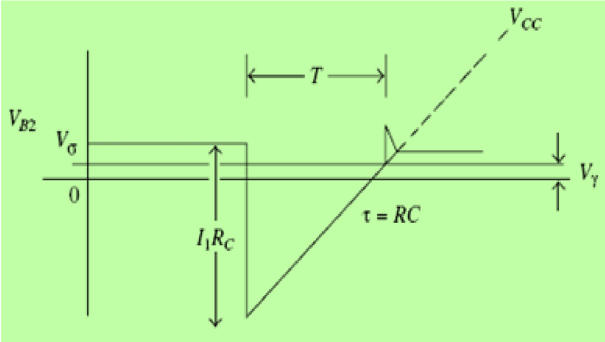

Figure 3.30 The voltage variation at the base of Q_2, in the quasi-stable state

However, at $t = T$, $V_{B2}(t) = V_{\gamma}$

$$V_{\gamma} = V_{CC} - [2V_{CC} - (V_{\sigma} + V_{CE(sat)}]e^{-T/\tau_1}$$

As

$$\frac{V_{\sigma} + V_{CE(sat)}}{2} \approx V_{\gamma}$$

$$T = \tau \ln 2 \frac{V_{CC} - V_{\gamma}}{V_{CC} - V_{\gamma}}$$

$T = 0.69\tau$ -- ----- 3.58

The time period T can be calculated as T = 0.69 RC, if $Q1$ in the quasi-stable state is in saturation.

EXAMPLE PROBLEM:

Example 3.4: Calculate the gate width for the monostable multivibrator given that $\boldsymbol{R}$ = 100 kΩ, $\boldsymbol{V_{CC}}$ = 10 V, $\boldsymbol{C}$ = 0.01 $\boldsymbol{\mu}$F.

Solution:

$\boldsymbol{\tau} = \boldsymbol{RC} = 100 \times 10^3 \times 0.01 \times 10^{-6} = 1$ ms

When $\boldsymbol{I_{CO}}$ is neglected, the gate width is calculated using Eq. (3.58),

$\boldsymbol{T} = 0.69 \times 100 \times 10^3 \times 0.01 \times 10^{-6} = 0.69$ ms.

3.6.2 Calculation of the Voltages to Plot the Waveforms:

To plot the waveforms at the two collectors and the two bases, the voltages in the circuit are to be calculated; when the multivibrator is in the stable state, when it is driven into the quasi-stable state and finally when it returns to the initial stable state. Consider the collector-coupled monostable multivibrator as shown in Figure 3.27.

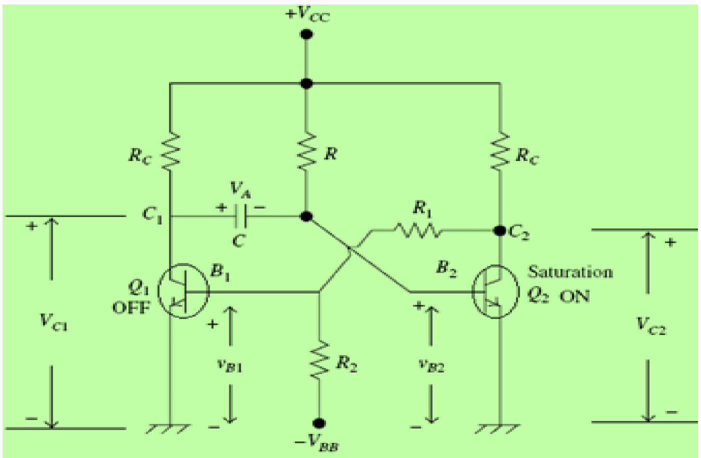

Figure 3.27 The collector-coupled monostable multivibrator

In the Stable State ($t < 0$)

Here, the assumption is that $\boldsymbol{Q}_2$ is ON and in saturation while $\boldsymbol{Q}_1$ is OFF. In this situation, the need is to verify whether $\boldsymbol{Q}_2$ is really in saturation or not and whether $\boldsymbol{Q}_1$ is in the OFF state.

To Verify that Q_2 is in Saturation.

For this we need to calculate $\boldsymbol{I}_{C2}$ and $\boldsymbol{I}_{B2}$ and then verify whether $\boldsymbol{I}_{B2}$ is significantly larger than $\boldsymbol{I}_{B2(\min)}$ or not. If $\boldsymbol{I}_{B2} >> \boldsymbol{I}_{B2(\min)}$, then $\boldsymbol{Q}_2$ is really in saturation. To verify this, consider the circuit shown in Figure 3.31(a).

From Figure 3.31(a),

$$I_2 = \frac{V_{CC} - V_{CE(sat)}}{R_C} - - - - - 3.59$$

$$I_3 = \frac{-V_{CE(sat)} - (-V_{BB})}{R_1 + R_2} - - - 3.60$$

$$\therefore I_{C2} = I_2 - I_3 - - - - - - - - 3.61$$

$$I_{B2} = \frac{V_{CC} - V_\sigma}{R} - - - - - - - - 3.62$$

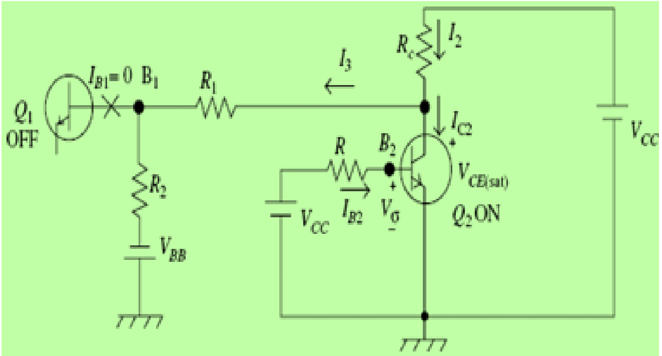

Figure 3.31(a) In the stable state Q_1 is OFF and Q_2 is ON

$$I_{B2\,min)} = \frac{I_{C2}}{h_{FE(min)}} - 3.63$$

For Q_2 to be in saturation, I_{B2} should be at least 1.5 $I_{B2(min)}$. If $I_{B2} >> I_{B2(min)}$, Q_2 is really in saturation, as per the assumption made. Hence $V_{C2} = V_{CE(sat)}$ and $V_{B2} = V_{BE(sat)} = V_\sigma$.

To Verify that Q_1 is OFF.

To show that $\boldsymbol{Q_1}$ is OFF, the voltage $\boldsymbol{V_{B1}}$ at $\boldsymbol{B_1}$ is to be found out and then checked whether the base–emitter diode is reverse-biased or not. If this diode is reverse-biased, then $\boldsymbol{Q_1}$ is OFF. To calculate the voltage $\boldsymbol{V_{B1}}$ at $\boldsymbol{B_1}$, consider the circuit shown in Figure 3.31(b). The voltage $\boldsymbol{V_{B1}}$ is due to the two sources; the $\boldsymbol{V_{BB}}$ source and the $\boldsymbol{V_{CE(sat)}}$ source. Use the superposition theorem to calculate $\boldsymbol{V_{B1}}$, considering one source at a time.

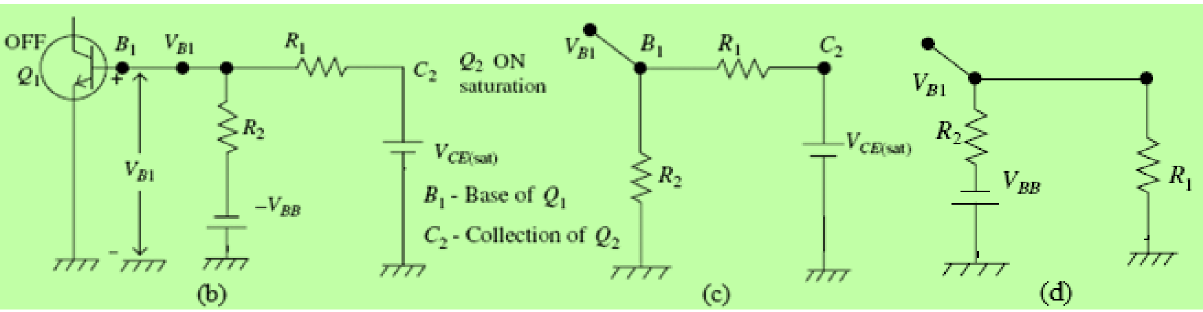

Figure 3.31 (b) The circuit for calculating V_{B1}, (c) The circuit to calculate V_{B1} due to V_{CE}(sat) source, (d) The circuit to calculate V_{B1} due to – V_{BB} source

Shorting the $\boldsymbol{V_{BB}}$ source, the resultant circuit is as shown in Figure 3.31(c).

So, $V_{B1}(V_{BB} = 0) = V_{CE(sat)} \times \frac{R_2}{R_1+R_2}$ -- 3.64

Now shorting the $V_{CE(sat)}$ source, the resultant circuit is as shown in Figure 3.31(d).

So, $V_{B1}(V_{EC(sat)} = 0) = -V_{BB} \times \frac{R_1}{R_1+R_2}$ -- 3.65

Combining Eqs. (3.64) and (3.65), the net voltage $\boldsymbol{V_{B1}}$ at $\boldsymbol{B_1}$ due to the two sources $\boldsymbol{V_{CE(sat)}}$ and $-\boldsymbol{V_{BB}}$ is:

$V_{B1} = V_{CE(sat)} \times \frac{R_2}{R_1+R_2} + (-V_{BB}) \times \frac{R_1}{R_1+R_2}$ ---3.66

If the base of Q_1 is negative with respect to the emitter, the base–emitter diode is reverse-biased. Therefore, Q_1 is OFF, as assumed. Hence, $V_{C1} = V_{CC}$. The voltage across the capacitor terminals is,

$V_A = V_{C1} - V_{B2} = V_{CC} - V\sigma$ --3.67

In the Quasi-stable State (*t* = *0*+):

At $\boldsymbol{t} = 0$, a negative pulse of proper amplitude is applied at the base of $\boldsymbol{Q_2}$ that drives $\boldsymbol{Q_2}$ into the OFF state. As a result $\boldsymbol{Q_1}$ goes into the ON state and into saturation as shown in Figure 3.31(e).

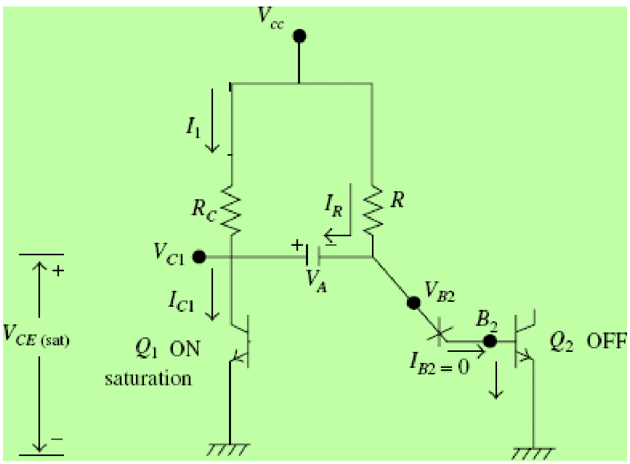

Figure 3.31(e) In the quasi-stable state Q_1 is ON and Q_2 is OFF

First let us verify whether Q_1 is really in saturation or not. Let us calculate I_{C1}.

$I_{C1} = I_1 + I_R$---3.68

$I_1 = \frac{V_{CC} - V_{CE(sat)}}{R_C}$ ---3.69

To calculate I_R, write the KVL equation of the loop consisting of R_C, C and R.

$I_R R = I_1 R_C + V_A$ ---3.70

Using Eqs. (8.19) and (8.20), we get $\boldsymbol{I_1}$ and $\boldsymbol{I_R}$.

Therefore,

$I_{B1(min)} = \frac{I_{C1}}{h_{FE(min)}}$ ---3.71

To Calculate I_{B1}: Considering Figure 3.31(f):

$I_{B1} = I_3 - I_4$ ----------------------------------3.72

$I_3 = \frac{V_{CC} - V_\sigma}{R_C + R_1}$ ---------------------------------3.73

$I_4 = \frac{V_\sigma - (-V_{BB})}{R_2}$ ---------------------------3.74

If $I_{B1} >> I_{B1(min)}$, then Q_1 is in saturation,

$V_{C2} = V_{CC} - I_3 R_C$ ---------------------------3.75

$V_{B2} = V_{CC} - I_R \times R$ ------------------------3.76

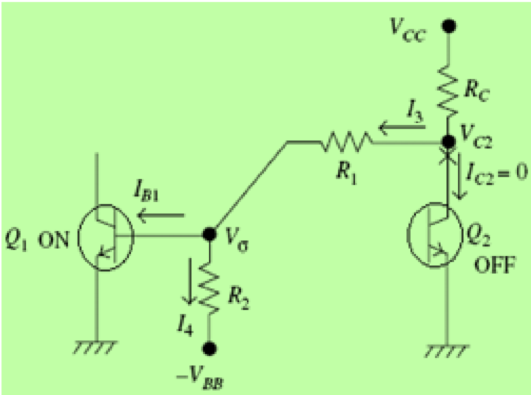

Figure 3.31(f) Circuit that is used to calculate I_{B1}

In the quasi-stable state, only V_{B2} changes and all other voltages remain unaltered. At $t = T$, when $V_{B2} = V_\gamma$, the quasi-stable state ends and the multivibrator returns to the initial stable condition of Q_1 and Q_2 in the OFF and ON states, respectively.

At the End of the Quasi-stable State (at $t = T+$):

At the end of the quasi-stable state, $\boldsymbol{Q}_1$ goes OFF and $\boldsymbol{Q}_2$ goes ON and into saturation. In this process, overshoots (increase over and above the expected value) can occur at the base of $\boldsymbol{Q}_2$ and at the collector of $\boldsymbol{Q}_1$, because the voltage change occurs abruptly. The amount of overshoot is accounted for by the base spreading resistance $\boldsymbol{r}_{\boldsymbol{bb'}}$ which is the resistance seen between the external base lead and the internal base terminal and is the resistance offered to a recombination current. This is typically less than 1 kΩ, as shown in Figure 3.31(g).

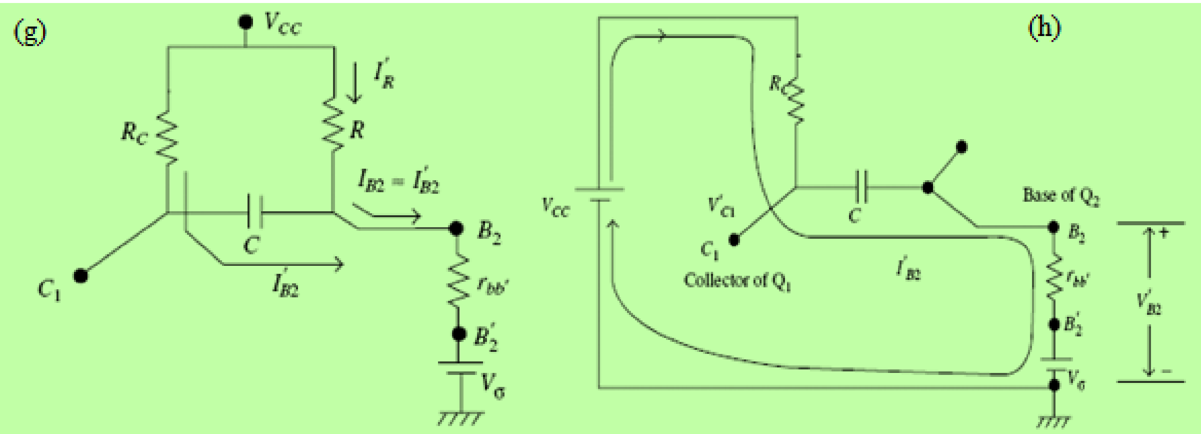

Figure 3.31(g) The circuit at the end of the quasi-stable state, (h) The simplified circuit of Figure 3.31(g)

From Figure 3.31(g),

$I_{B2} = I'_{B2} - I'_R$ ---3.77

As $R >> R_C$, $I'_R << I'_{B2}$---3.78

Neglecting the current $\boldsymbol{I_R}$ when compared to I'_{B2} the circuit reduces to as shown in Figure 3.31(h).

The voltages at $\boldsymbol{B}_2$ and $\boldsymbol{C}_1$ are

$V'_{B2} = I'_{B2}\ r_{bb'} + V_\sigma$---3.79

$V_{C1}^{|} = \ V_{CC} - \ I_{B2}^{|} \ R_C$ ---3.80

The overshoot δ at the second base is the variation over and above $V\gamma$.

$$\delta = V_{B2}^{|} - V_{\gamma}$$

Using Eq. (3.79):

$\delta = V_{B2}^{|} - V_{\gamma} = I_{B2}^{|} \ r_{bb^{|}} + V_{\sigma} - V_{\gamma}$---3.81

Similarly the overshoot δ' at the first collector is the variation over and above $V_{CE(\text{sat})}$

Therefore,

$$\delta^{|} = V_{C1}^{|} - V_{CE(sat)}$$

Using Eq. (8.31):

$\delta^{|} = V_{CC} - I_{B2}^{|} \ R_C - V_{CE(sat)}$ ---3.82

The first collector and the second base are connected through a condenser C and as the condenser will not allow any sudden changes in the voltages, whatever is the change that takes place at the first collector an identical change is required to take place at the second base. Hence, $\delta = \delta'$ and from equations 3.81 & 3.82, we get

$$I_{B2}^{|} \ r_{bb^{|}} + V_{\sigma} - V_{\gamma} \ = \ V_{CC} - I_{B2}^{|} \ R_C - V_{CE(sat)}$$
$$I_{B2}^{|} \ (\ r_{bb^{|}} + R_C) \ = \ V_{CC} - V_{CE(sat)} + V_{\sigma} - V_{\gamma}$$

$\therefore \ I_{B2}^{|} \ = \ \frac{V_{CC} - V_{CE(sat)} + V_{\sigma} - V_{\gamma}}{r_{bb^{|}} + R_C}$ ---3.83

$V_{C1}^{|} = V_{CC} - I_{B2}^{|} R_C$ --3.84

$V_{B2}^{|} = I_{B2}^{|} r_{bb^{|}} + V_{\sigma}$ ---3.85

The waveforms can now be plotted. To plot the waveforms of a collector-coupled monostable multivibrator with specific component values mentioned, consider the following example.

EXAMPLE PROBLEM:

Example 3.5: Consider the circuit shown in Figure 3.32(a), which uses an ***n–p–n*** silicon transistors with the following specifications: V_{CC} = 10 V, V_{BB} = 10 V, R_C = 1 kΩ, R_1 = 10 kΩ = R, R_2 = 100 kΩ, $h_{FE(min)}$ = 30, r_{bb} = 0.2 kΩ, $V_{CE(sat)}$ = 0.3 V, $V_{BE(sat)} = V_\sigma$ = 0.7 V. Calculate all the current and voltages and then plot the waveforms.

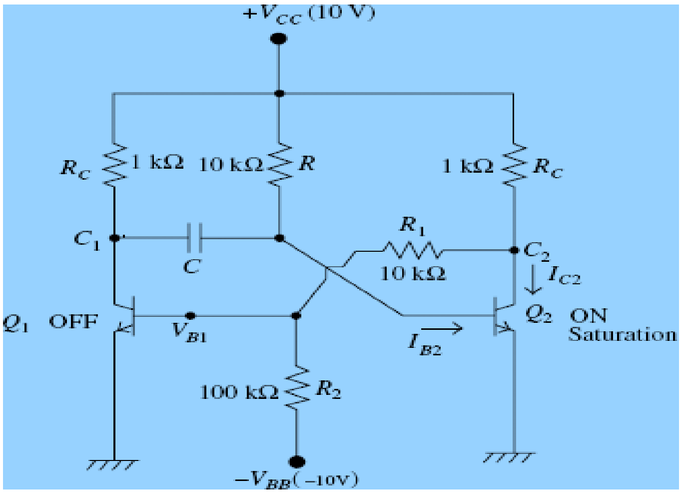

Figure 3.32(a) Practical collector-coupled monostable multivibrator

Solution: (i) In the stable state (t < 0), The assumption made is Q_2 is ON and in saturation and Q_1 is OFF. To verify that Q_2 is ON and in saturation, I_{C2} and I_{B2} of Q_2 are to be calculated. Further check whether $I_{B2} >> I_{B2(min)}$ or not. If $I_{B2} >> I_{B2(min)}$, then Q_2 is really in saturation. Consider the circuit shown in Figure 3.32(b).

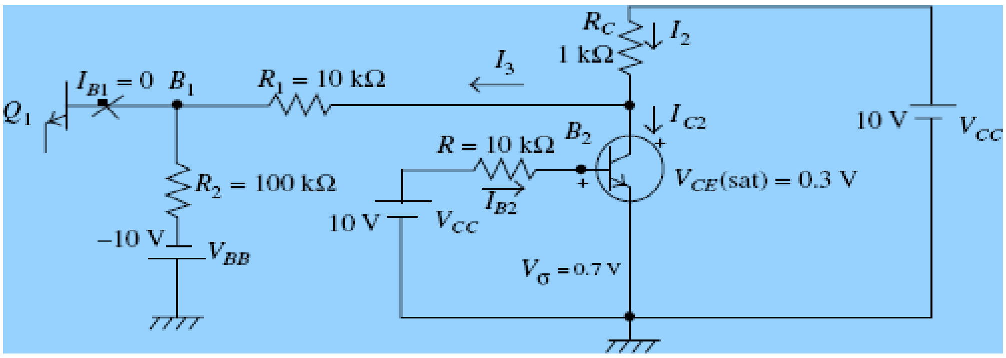

Figure 3.32(b) In the stable state, Q_1 is OFF and Q_2 is ON

(a) To verify if Q_2 is ON and in saturation:

$$I_{C2} = I_2 - I_3 \qquad I_2 = \frac{V_{CC} - V_{CE(\mathrm{sat})}}{R_C} = \frac{10 - 0.3}{1\,\mathrm{k}\Omega} = 9.7\,\mathrm{mA}$$

$$I_3 = \frac{V_{CE(\mathrm{sat})} - (-V_{BB})}{R_1 + R_2} = \frac{10.3}{110\,\mathrm{k}\Omega} = 0.0934\,\mathrm{mA}$$

$\therefore I_{C2} = I_2 - I_3 = 9.7\text{ mA} - 0.0934\text{ mA} = 9.61\text{ mA}$

$$I_{B2} = \frac{V_{CC} - V_{\sigma}}{R} = \frac{10 - 0.7}{10\,\mathrm{k}\Omega} = 0.93\,\mathrm{mA} \qquad I_{B2\,(\mathrm{min})} = \frac{I_{C2}}{h_{FE\,(\mathrm{min})}} = \frac{9.61\,\mathrm{mA}}{30} = 0.32\,\mathrm{mA}$$

For Q_2 to be in saturation, I_{B2} should be at least $1.5I_{B2(\mathrm{min})}$. Hence, I_{B2} should be selected to keep Q_2 in saturation as

$$I_{B2} = 1.5 \times 0.32\text{ mA} = 0.48\text{ mA}.$$

As $\boldsymbol{I_{B2}}$(0.93 mA) >> 1.5$\boldsymbol{I_{B2(\mathrm{min})}}$(0.48 mA), as per the assumption made $\boldsymbol{Q_2}$ is really in saturation. Hence,

$$\boldsymbol{V_{C2}} = 0.3\text{ V, and } \boldsymbol{V_{B2}} = 0.7\text{ V.}$$

b) To verify that $\boldsymbol{Q_1}$ is OFF:

To verify whether $\boldsymbol{Q_1}$ is in the OFF state or not, $\boldsymbol{V_{B1}} = \boldsymbol{V_{BE1}}$ is calculated and seen if it reverse-biases the base–emitter diode. The voltage $\boldsymbol{V_{B1}}$ is due to two sources—the $\boldsymbol{V_{BB}}$ source and the $\boldsymbol{V_{CE(\mathrm{sat})}}$ source, as shown in Figure 3.32(c). Use the superposition theorem to calculate $\boldsymbol{V_{B1}}$, considering one source at a time. Considering the $\boldsymbol{V_{CE(\mathrm{sat})}}$ source and shorting the $\boldsymbol{V_{BB}}$ source, the resultant circuit is as shown in Figure 3.32(d).

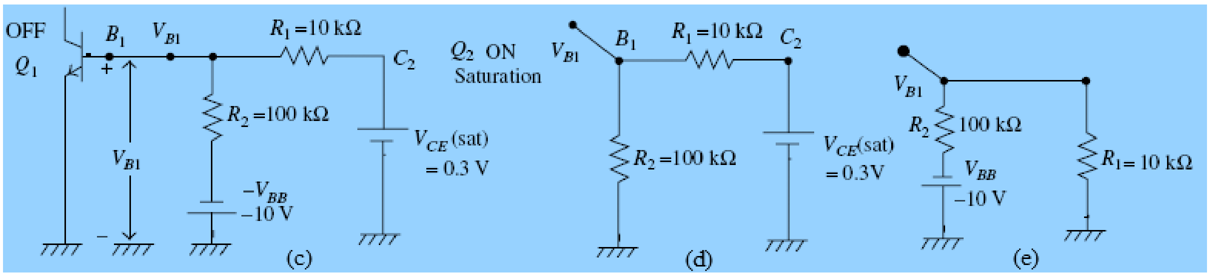

Figure 3.32 (c) The circuit for calculating V_{B1}, (d) The circuit to calculate V_{B1} due to $V_{CE(\mathrm{sat})}$ source, (e) Circuit to calculate V_{B1} due to $-V_{BB}$ source

$$V_{B1}(V_{BB} = 0) = V_{CE(\mathrm{sat})} \times \frac{R_2}{R_1 + R_2} = 0.3 \times \frac{100}{100 + 10} = \frac{3}{11} = 0.27\,\mathrm{V}$$

Now shorting the $\boldsymbol{V_{CE(\mathrm{sat})}}$ source, the resultant circuit is as shown in Figure 3.32(e).

$$V_{B1}(V_{CE(\mathrm{sat})} = 0) = -10 \times \frac{10}{110} = \frac{-10}{11} = -0.91\,\mathrm{V}$$

Therefore, the net voltage $\boldsymbol{V_{B1}}$ at $\boldsymbol{B_1}$ due to the two sources $\boldsymbol{V_{CE(\text{sat})}}$ and $-\boldsymbol{V_{BB}}$ is

$$\boldsymbol{V_{B1}} = 0.27 - 0.91 = -0.64 \text{ V}.$$

This explains that the base of Q_1 is negative with respect to the emitter by 0.64 V. Hence, the base–emitter diode is reverse-biased. Therefore, Q_1 is OFF, as assumed. Hence, $V_{C1} = V_{CC} = 10$ V. The voltage across the capacitor terminals is

$$V_A = V_{C1} - V_{B2} = V_{CC} - V\sigma = 10 \text{ V} - 0.7 \text{ V} = 9.3 \text{ V}$$

In the stable state, the voltages are $V_{B1} = -0.64$ V, $V_{C1} = 10$ V, $V_{B2} = 0.7$ V, $V_{C2} = 0.3$ V, $V_A = 9.3$ V.

ii) In the quasi-stable state ($\boldsymbol{t} = 0+$)

In the quasi-stable state, $\boldsymbol{Q_2}$ is driven into the OFF state, by the application of a trigger. Consequently, $\boldsymbol{Q_1}$ goes into the ON state and into saturation as shown in Figure 3.32 (f).

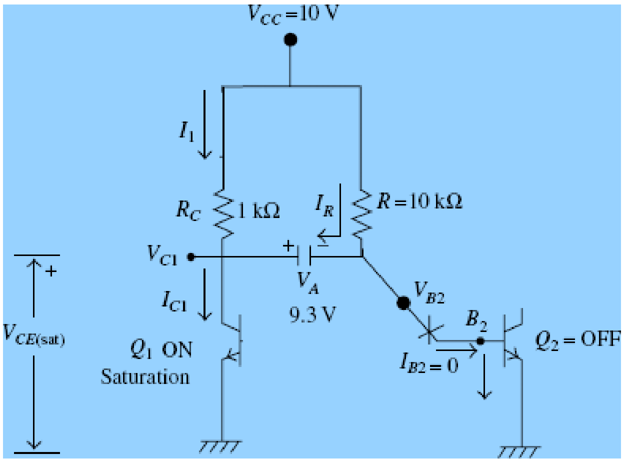

Figure 3.32 (f) In the quasi-stable state, Q_1 is ON and Q_2 is OFF

a) To verify if Q_1 is ON and in saturation or not

To verify whether Q_1 is really in saturation or not, calculate I_{C1}.

$$I_{C1} = I_1 + I_R \qquad I_1 = \frac{V_{CC} - V_{CE(\text{sat})}}{R_C} = \frac{10 - 0.3}{1 \text{ k}\Omega} = 9.7 \text{ mA}$$

To calculate I_R the KVL equation of the loop consisting of R_C, C and R is,

$$\boldsymbol{I_R R} = \boldsymbol{I_1 R_C} + \boldsymbol{V_A} = 9.7 \text{ V} + 9.3 \text{ V} = 19 \text{ V}$$

$$I_R = \frac{19 \text{ V}}{10 \text{ k}\Omega} = 1.9 \text{ mA}$$

Therefore,

$$\boldsymbol{I_{C1}} = \boldsymbol{I_1} + \boldsymbol{I_R} = 9.7 \text{ mA} + 1.9 \text{ mA} = 11.6 \text{ mA}$$

$$I_{B1(\min)} = \frac{I_{C1}}{h_{FE\ \min}} = \frac{11.6\text{ mA}}{30} = 0.39\text{ mA}$$

To calculate $\boldsymbol{I_{B1}}$, consider Figure 3.32(g).

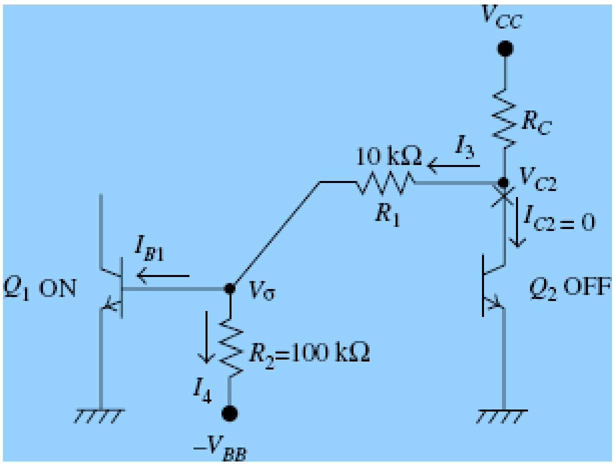

Figure 3.32(g) The circuit that is used to calculate $\boldsymbol{I_{B1}}$

$$I_{B1} = I_3 - I_4$$

$$I_3 = \frac{V_{CC} - V_\sigma}{R_C + R_1} = \frac{10 - 0.7}{1 + 10} = \frac{9.3\text{ V}}{11\text{ k}\Omega} = 0.84\text{ mA}$$

$$I_4 = \frac{V_\sigma - (-V_{BB})}{R_2} = \frac{0.7 + 10}{100\text{ k}\Omega} = \frac{10.7\text{ V}}{100\text{ k}\Omega} = 0.11\text{ mA}$$

$$I_{B1} = 0.84 - 0.11 = 0.73\text{ mA}$$

As already calculated, $I_{B1(\min)} = 0.39$ mA. Thus, $I_{B1} >> I_{B1(\min)}$.

Hence, Q_1 is in saturation.

$$\therefore V_{C1} = 0.3\text{ V},\ V_{B1} = 0.7\text{ V},$$

$$V_{C2} = V_{CC} - I_3R_C = 10 - (0.84)(1) = 9.16\text{ V}$$

$$V_{B2} = V_{CC} - I_RR = 10 - (1.9)(10) = -9\text{ V}$$

In the quasi-stable state, except $\boldsymbol{V_{B2}}$—which changes exponentially as a function of time—all other voltages remain unaltered. At $\boldsymbol{t} = \boldsymbol{T}$, when $\boldsymbol{V_{B2}} = \boldsymbol{V_\gamma}$, the quasi-stable state ends and the multivibrator returns to its initial stable condition. The voltages at the beginning of the quasi-stable state are $\boldsymbol{V_{C1}} = 0.3$ V, $\boldsymbol{V_{B1}} = 0.7$ V, $\boldsymbol{V_{C2}} = 9.16$ V, $\boldsymbol{V_{B2}} = -9$ V initially and varies exponentially.

iii) At the end of the quasi-stable state (at $\boldsymbol{t} = \boldsymbol{T}$ +)

At the end of the quasi-stable state $\boldsymbol{Q_1}$ goes OFF and $\boldsymbol{Q_2}$ goes ON and into saturation, resulting in overshoots at the base of $\boldsymbol{Q_2}$ and at the collector of $\boldsymbol{Q_1}$. The overshoots are calculated using Figure 3.32(h).

Neglecting the current I_R when compared to $I^{|}_{B2}$ the circuit reduces to Figure 3.32(i).

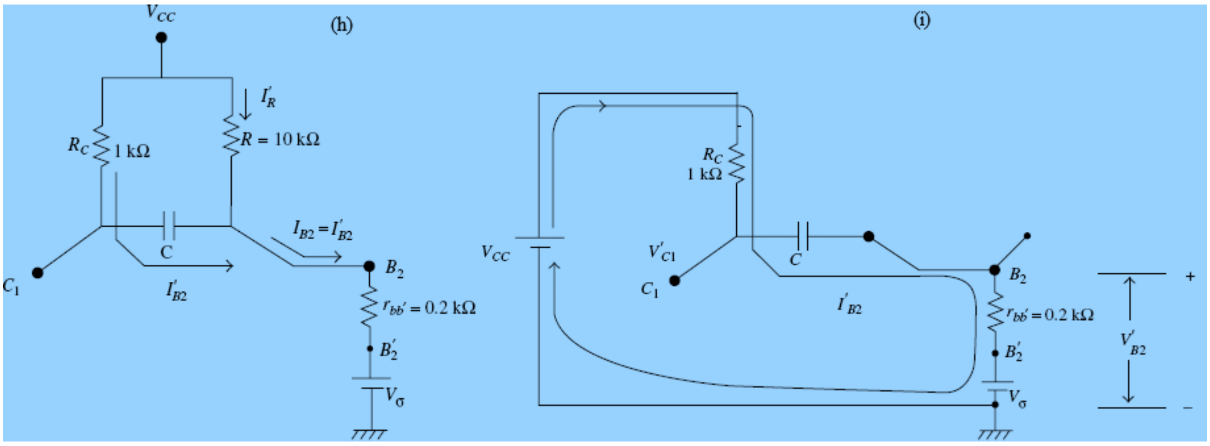

Figure 3.32 (h) The circuit that is used to calculate I_{B1}, (i) The simplified circuit of Figure 3.32(h)

Using Eq. (3.83):

$$I'_{B2} = \frac{V_{CC} - V_{CE(\text{sat})} - V_\sigma + V_\gamma}{r_{bb'} + R_C}$$

$$= \frac{10 - 0.3 - 0.7 + 0.5}{0.2 + 1} = \frac{9.5\text{ V}}{1.2\text{ k}\Omega}$$

$$I^{|}_{B2} = 7.91\text{ mA}$$

$$V^{|}_{C1} = \boldsymbol{V_{CC}} - I'_{B2}\boldsymbol{R_C} = 10 - (7.91)(1) \rightarrow V^{|}_{C1} = 2.09\text{ V}$$

$$V^{|}_{B2} = I^{|}_{B2}\boldsymbol{r_{bb'}} + \boldsymbol{V_\sigma} = (7.91)(0.2) + 0.7 = 1.58 + 0.7 \rightarrow V^{|}_{B2} = 2.28\text{ V}$$

At $t = T+$, the voltages are V_{C2} = 0.3 V, V_{B2} = 2.28 V, V_{C1} = 10 V, V_{B1} = −0.64 V. The waveforms are plotted as shown in Figure 3.32 (j).

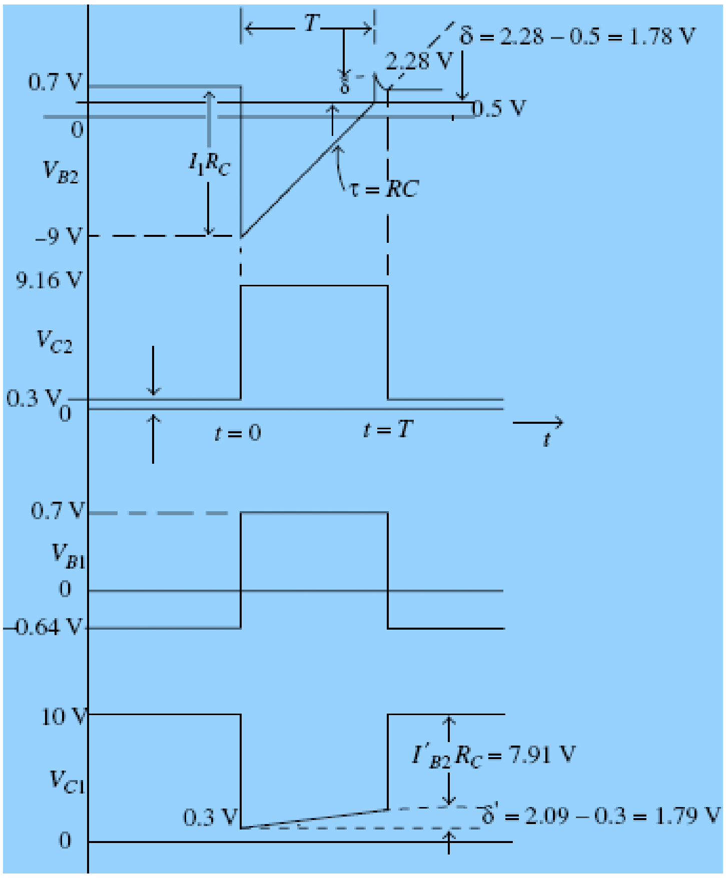

Figure 3.32 (j) Waveforms of the collector-coupled monostable

3.6.3 The Design of a Collector-coupled Monostable Multivibrator

Let us design a collector-coupled monostable multivibrator of Figure 3.27, having a gate width ***T***. From the circuit of Figure 3.27 we have,

$$R_C = \frac{V_{CC} - V_{CE(sat)}}{I_{C(sat)}}$$ ----------------------- - 3.86

$$I_{B(\min)} = \frac{I_{C1(sat)}}{h_{FE(min)}}$$ ----------------------- - 3.87

Select $I_{B(\mathrm{sat})} = 2 \times I_{B(\min)}$

$$R = \frac{V_{CC} - V_{\sigma}}{I_{B(sat)}}$$ ----------------------------- - 3.88

For ON device to be in saturation:

$$R \le h_{FE} R_C$$ ---------------------------- - 3.89

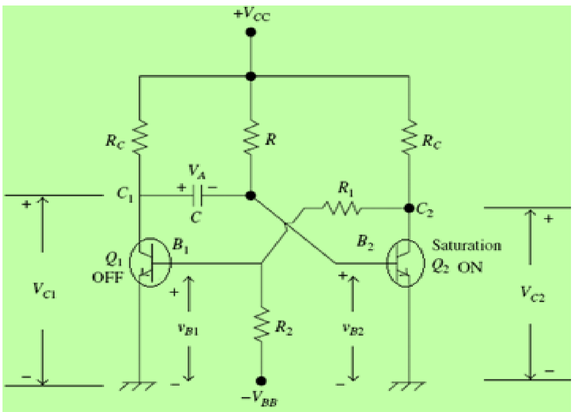

Figure 3.27 The collector-coupled monostable multivibrator

On verifying whether the condition in Eq. (3.89) is satisfied or not; the value of $\boldsymbol{R}$ is accepted (if satisfying). If not, the value of $\boldsymbol{R}$ is changed suitably, to satisfy the Eq. (3.89).

Assuming that the current in $\boldsymbol{R}_2$ is $\boldsymbol{I}_2$:

$$I_2 \approx \frac{1}{10} I_C$$

$R_2 = \frac{V_\sigma + V_{BB}}{I_2}$ -- 3.90

When $\boldsymbol{Q}_1$ is ON, if $\boldsymbol{I}_1$ is the current in ($\boldsymbol{R_C}$ + $\boldsymbol{R}_1$):

$I_1 = I_{B1} + I_2$ -- 3.91

$R_C + R_1 = \frac{V_{CC} - V_\sigma}{I_1}$ -- 3.92

$$\boldsymbol{R}_1 = (\boldsymbol{R_C} + \boldsymbol{R}_1) - \boldsymbol{R_C}$$

Using the relation, $\boldsymbol{T} = 0.69\boldsymbol{RC}$, the value of $\boldsymbol{C}$ is calculated. To understand the design procedure let us consider an example 3.6.

EXAMPLE PROBLEM

Example 3.6: Design a collector-coupled monostable circuit of Figure 3.27 to generate a pulse of width 100 $\boldsymbol{\mu}$s. Silicon devices with $\boldsymbol{h_{FE}}_{(\text{min})} = 50$ are used. ON device is in saturation.

Given that: $\boldsymbol{V_{CC}}$ = 12V, $\boldsymbol{V_{CE}}_{(\text{sat})}$ = 0.2 V, $\boldsymbol{V_{BE}}_{(\text{sat})}$ = 0.7 V, $\boldsymbol{I_B}_{(\text{sat})} = 2\,\boldsymbol{I_B}_{(\text{min})}$, $\boldsymbol{V_{BB}}$ = 12 V, $\boldsymbol{I_C}_{(\text{sat})}$ = 2 mA, $\boldsymbol{T}$ = 100 $\boldsymbol{\mu}$s.

Solution:

1. Let $\boldsymbol{Q}_2$ be ON and $\boldsymbol{Q}_1$ be OFF.

$$R_{C2} = \frac{V_{CC} - V_{CE(\text{sat})}}{I_{C2(\text{sat})}} = \frac{12 - 0.2}{2\,\text{mA}} = \frac{11.8}{2\,\text{mA}} = 5.9\,\text{k}\Omega \approx 6\,\text{k}\Omega$$

$$I_{B2\,(\text{min})} = \frac{I_{C2(\text{sat})}}{h_{FE\,(\text{min})}} = \frac{2\,\text{mA}}{50} = 40\,\mu\text{A}$$

$\boldsymbol{I_B}_{2(\text{sat})} = 2 \times \boldsymbol{I_{B}}_2\,(\text{min}) = 2 \times 40 = 80\,\boldsymbol{\mu}$A

$$R = \frac{V_{CC} - V_\sigma}{I_{B2(\text{sat})}} = \frac{12 - 0.7}{80\,\mu\text{A}} = \frac{11.3}{80 \times 10^{-6}} = \frac{1130}{8} \times 10^3 = 141\,\text{k}\Omega$$

$\boldsymbol{h_{FE}R_C} = 50 \times 6 = 300$ kΩ

For ON device to be in saturation,

$\boldsymbol{R} \leq \boldsymbol{h_{FE} R_C}$

Hence, the condition is verified.

2. When $\boldsymbol{Q}_1$ is ON, let $\boldsymbol{I}_2$ be the current in $\boldsymbol{R}_2$.

$$I_2 \approx \frac{1}{10} I_{C(\mathrm{sat})} = 0.2\,\mathrm{mA} \qquad R_2 = \frac{V_\sigma + V_{BB}}{I_2} = \frac{12.7}{0.2} = 63.5\,\mathrm{k\Omega}$$

Let $\boldsymbol{I}_1$ be the current in $\boldsymbol{R_C} + \boldsymbol{R}_1$.

$\boldsymbol{I}_1 = \boldsymbol{I_{B1}} + \boldsymbol{I}_2 = 0.08 + 0.2 = 0.28$ mA

$$R_C + R_1 = \frac{V_{CC} - V_\sigma}{I_1} = \frac{12 - 0.7}{0.28\,\mathrm{mA}} = 40\,\mathrm{k\Omega}$$

$\boldsymbol{R}_1 = (\boldsymbol{R_C} + \boldsymbol{R}_1) - \boldsymbol{R_C} = 40 - 6 = 34$ kΩ

$\boldsymbol{T} = 0.69\boldsymbol{R}\mathrm{C} \qquad 100 \times 10^{-6}\ \boldsymbol{s} = 0.69 \times 141 \times 10^3 \times \boldsymbol{C}$

$$C = \frac{100 \times 10^{-6}}{0.69 \times 141 \times 10^3} = \frac{100}{7 \times 14} \times 10^{-9} \approx 1\,\mathrm{nF}$$

ASTABLE MULTIVIBRATORS

3.7 INTRODUCTION

Multivibrators are switching circuits that employ positive feedback by cross-coupling the output of one stage to the input of the other stage, such that if one device is ON, the other is OFF. In astable multivibrators, the interchange of states is possible by internal capacitive coupling. An astable multivibrator is basically a square-wave generator.

A transistor Q_1 or Q_2 is said to be in the stable state, if it is either ON or OFF permanently. If the state of the device, say Q_1, changes from ON to OFF, and automatically returns to the ON state after a time duration, the device is said to be in the quasi-stable state for this specified time interval. The devices in this multivibrator will not remain in any one state (ON or OFF) forever. The change of state in the device occurs automatically after a finite time interval, depending on the circuit components employed. Hence, this circuit has two quasi-stable states.

In an astable multivibrator, if Q_1 is ON, then Q_2 is OFF; and they will remain in this state for a limited time duration, after which Q_1 automatically switches into the OFF state and Q_2 into the ON state and so on. The output of the circuit is a square wave with two time periods, T_1 and T_2. If $T_1 = T_2 = T/2$ the circuit is a symmetric astable multivibrator. If $T_1 = T_2$, it is called an un-symmetric astable multivibrator. The main application of an astable multivibrator is as a clock in digital circuits. The astable multivibrator is essentially a square-wave generator (oscillator). We consider two circuits: the collector-coupled astable multivibrator and the emitter-coupled astable multivibrator in the following sections.

3.8 COLLECTOR-COUPLED ASTABLE MULTIVIBRATORS:

A collector-coupled astable multivibrator is shown in Figure 3.33. Here, there is a cross-coupling from the second collector to the first base and also a cross-coupling from the first collector to the second base. This means that the output of one device is the input for the other. While analyzing the functioning of this circuit, it is

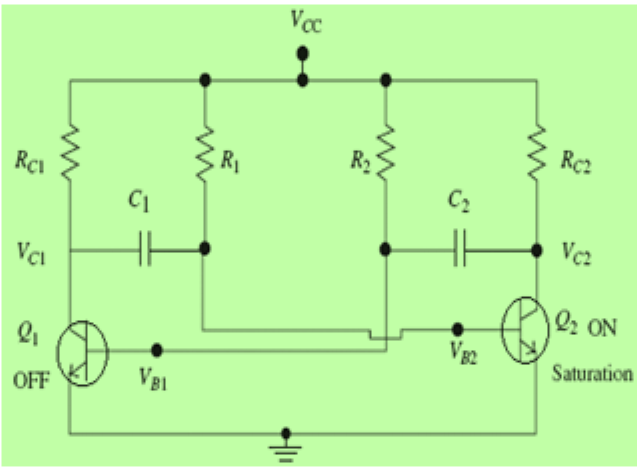

Figure 3.33 A collector-coupled astable

assumed that the circuit is an oscillator; and working backwards, we can justify that it does indeed oscillate.

multivibrator

Let us assume that at the given instant of time $\boldsymbol{Q}_1$ is OFF and $\boldsymbol{Q}_2$ is ON and saturated. Then $\boldsymbol{V}_{\boldsymbol{B}2} = \boldsymbol{V}_{\boldsymbol{\sigma}}$, $\boldsymbol{V}_{\boldsymbol{C}2} = \boldsymbol{V}_{\boldsymbol{CE}(\mathrm{sat})}$ and $\boldsymbol{V}_{\boldsymbol{C}1} = \boldsymbol{V}_{\boldsymbol{CC}}$. With $\boldsymbol{Q}_1$ OFF and $\boldsymbol{Q}_2$ ON, $\boldsymbol{C}_1$ will try to charge to the supply voltage through the collector resistance $\boldsymbol{R}_{\boldsymbol{C}1}$ and the small resistance of $\boldsymbol{Q}_2$ ($\approx \boldsymbol{r}_{\boldsymbol{bb'}}$), as shown in Figure 3.34(a). However, prior to this condition, $\boldsymbol{Q}_2$ must have been in the OFF state and $\boldsymbol{Q}_1$ must have been in the ON state. As a result, $\boldsymbol{C}_2$ must have been charged through $\boldsymbol{R}_{\boldsymbol{C}2}$ and $\boldsymbol{r}_{\boldsymbol{bb'}}$ of $\boldsymbol{Q}_1$, as shown in Figure 3.34(b).

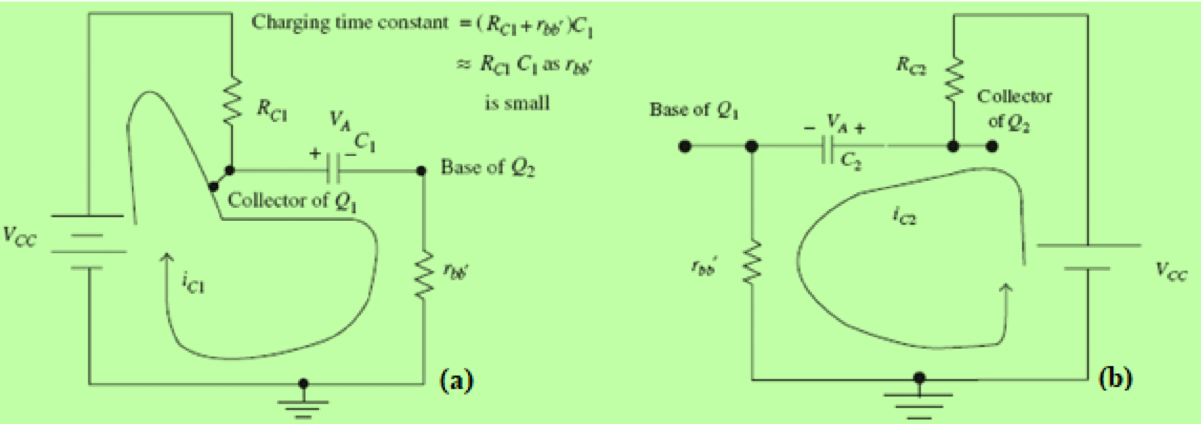

Figure 3.34 (a) The charging of the capacitor C_1, (b) The charging of capacitor C_2

When $\boldsymbol{Q}_2$ suddenly switches from the OFF state into the ON state, the voltage between its collector and emitter terminals is $\boldsymbol{V}_{\boldsymbol{CE}}$ ($\approx$0 V). Hence, the collector of $\boldsymbol{Q}_2$ is at ground potential, i.e., the positive end of the capacitor $\boldsymbol{C}_2$ is at the ground potential and its negative terminal is connected to the base of $\boldsymbol{Q}_1$. As a large negative voltage is now coupled to the base of $\boldsymbol{Q}_1$, it is in the OFF state (see Figure 3.34(c)). However, $\boldsymbol{Q}_1$ will not remain in the OFF state forever. Now, with $\boldsymbol{Q}_2$ ON, the charge on the condenser $\boldsymbol{C}_2$ discharges with a time constant $\boldsymbol{\tau}_2 = \boldsymbol{R}_2\boldsymbol{C}_2$.

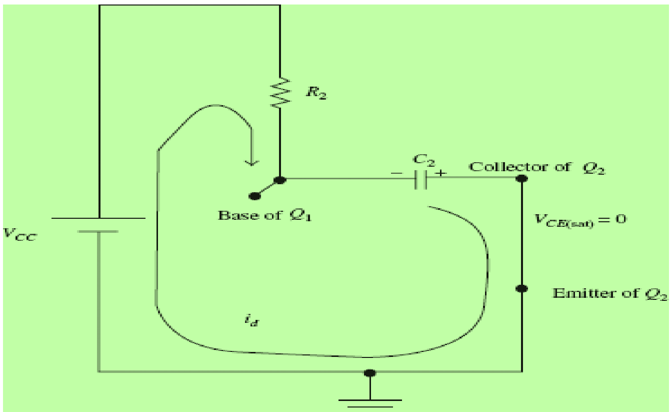

Figure 3.34 (c) The discharge of C_2 through R_2

As a result, the voltage at the base of $\boldsymbol{Q}_1$ goes on changing as a function of time. Once this voltage reaches $\boldsymbol{V}_\gamma$, $\boldsymbol{Q}_1$ starts drawing base current. Hence, there is a collector current. In turn, there is voltage drop across $\boldsymbol{R}_{C1}$ and the voltage at the collector of $\boldsymbol{Q}_1$ falls. This voltage was earlier $\boldsymbol{V}_{CC}$ and now, it is smaller than $\boldsymbol{V}_{CC}$. Therefore, the negative step at this collector is coupled to the base of $\boldsymbol{Q}_2$ through $\boldsymbol{C}_1$. As the collector of $\boldsymbol{Q}_1$ and the base of $\boldsymbol{Q}_2$ are connected through $\boldsymbol{C}_1$ and the capacitor will not allow any sudden changes in the voltage, the base of $\boldsymbol{Q}_2$ undergoes changes that are identical to those that have taken place at the first collector. As a result, the base and collector current of $\boldsymbol{Q}_2$ drop; so, the collector voltage rises. This positive step change is coupled to the base of $\boldsymbol{Q}_1$; and thus, its base current increases further. And the collector current increases, the voltage at the collector of $\boldsymbol{Q}_1$ falls still further. This step change is coupled to the base $\boldsymbol{Q}_2$ and this process is repeated. Thus, a regenerative action takes place and $\boldsymbol{Q}_2$ switches to the OFF state and $\boldsymbol{Q}_1$ goes into the ON state. Hence, the circuit oscillates. As long as the voltage at the base is $\boldsymbol{V}_\sigma$, the voltage at the collector is $\boldsymbol{V}_{CE(\mathrm{sat})}$. Once the voltage at the base is negative, the device switches into the OFF state, giving rise to a voltage $\boldsymbol{V}_{CC}$ at its collector.

The waveforms at the two bases and the two collectors are shown in Figure 3.34(d). When a transistor, say Q_1, switches from the ON state into the OFF state, its collector voltage is required to abruptly rise to V_{CC}. Consequently, the waveforms at the collectors should have sharp rising edges and flat tops. But when Q_1 goes into the OFF state and Q_2 into the ON, there is a charging current of the condenser C_1 which prevents the sudden rise of the voltage from V_{C1} to V_{CC}. Only when this charging current is zero does the collector voltage reach V_{CC}.

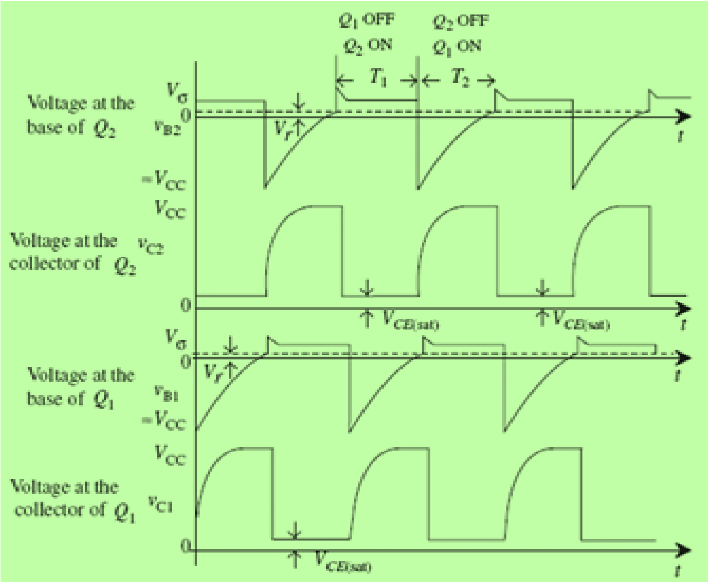

Figure 3.34 (d) The waveforms of a collector-coupled astable multivibrator

3.8.1 Calculation of the Frequency of an Astable Multivibrator

To calculate the frequency (*f*), the two time periods T_1 and T_2 are to be calculated. Then:

$T = T_1 + T_2$ and f=1/T. To calculate T, we calculate T_1 and T_2. Consider the waveform at the base of Q_2, as shown in Figure 3.35.

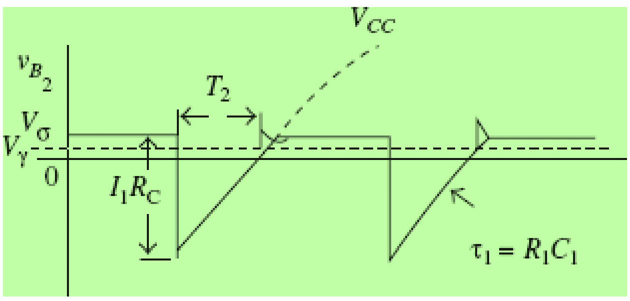

Figure 3.35 Voltage variation at the base of Q_2

In general, the voltage variation at the base of Q_2 as a function of time is given by the relation:

$$v_{B2}(t) = v_f - (v_f - v_i)e^{-t/\tau} \qquad \text{------------ 3.93}$$

Here, $v_f = V_{CC}$, $v_i = V_\sigma - I_1R_C$ and the time constant, $\tau_1 = R_1C_1$.

$$v_{B2}(t) = V_{CC} - (V_{CC} - V_\sigma + I_1R_C)e^{-t/\tau_1} \qquad \text{------------ 3.94}$$

But, at $t = T_2$, $v_{B2}(t) = V_\gamma$

$$\therefore V_\gamma = V_{CC} - (V_{CC} - V_\sigma + I_1R_C)\, e^{-T_2/\tau_1}$$

Hence,

$$T_2 = \tau_1 ln\left(\frac{V_{CC} - V_\sigma + I_1R_C}{V_{CC} - V_\gamma}\right) \qquad \text{------------ 3.95}$$

Similarly,

$$T_1 = \tau_2 ln\left(\frac{V_{CC} - V_\sigma + I_2R_C}{V_{CC} - V_\gamma}\right) \qquad \text{------------ 3.96}$$

where, $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ are the currents in $\boldsymbol{Q}_1$ and $\boldsymbol{Q}_2$ when ON. However, here, in the expressions for $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$, the currents $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ are present (for all practical purposes these two currents are the same, if the devices have identical parameters).

To ensure that $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ remain constant, the ON device is preferably driven into saturation. Consider the expression for $\boldsymbol{T}_2$ from Eq. (3.95):

$$T_2 = \tau_1 ln\left(\frac{V_{CC} - V_\sigma + I_1R_C}{V_{CC} - V_\gamma}\right)$$

If $\boldsymbol{Q}_1$, in the quasi-stable state, is in saturation, then:

$$I_1R_C = V_{CC} - V_{CE(sat)} \qquad \text{--- 3.97}$$

$$T_2 = \tau_1 ln\left(\frac{V_{CC} - V_\sigma + V_{CC} - V_{CE(sat)}}{V_{CC} - V_\gamma}\right) = \tau_1 ln\left(\frac{2V_{CC} - (V_\sigma + V_{CE(sat)})}{V_{CC} - V_\gamma}\right)$$

$$T_2 = \tau_1 \ln 2 \times \left(\frac{V_{CC} - \left(\frac{V_\sigma + V_{CE(sat)}}{2} \right)}{V_{CC} - V_\gamma} \right)$$

But, $\left(\frac{V_\sigma + V_{CE(sat)}}{2} \right) \approx V_\gamma$ -- 3.98

Therefore,

$T_2 = \tau_1 \ln 2 \left(\frac{V_{CC} - V_\gamma}{V_{CC} - V_\gamma} \right) = \tau_1 \ln 2 + \tau_1 ln \left(\frac{V_{CC} - V_\gamma}{V_{CC} - V_\gamma} \right) = \tau_1 \ln 2 + \ln 1 = \tau_1 \ln 2 + 0 = 0.69\, \tau_1$

Similarly,

$T_1 = 0.69\, \tau_2$ -- 3.99

T_1 and T_2 are now stable.

Therefore,

$T = 0.69\, (\tau_1 + \tau_2)$ --- 3.100

In a symmetric astable multivibrator, $\tau_1 = \tau_2 = \tau$

Therefore,

$T = 1.4\, \tau$ -- 3.101

and

$f = \frac{1}{1.4\, \tau} = \frac{0.7}{\tau}\; c/s$ -- 3.102

3.8.2 The Design of an Astable Multivibrator

Let us now try to design the astable multivibrator shown in Figure 3.36. We are now required to fix the component values of the astable multivibrator shown in Figure 3.36. For this to happen, we have to know $\boldsymbol{h_{FE}}_{(\min)}$, $\boldsymbol{I_C}_{(\text{sat})}$, $\boldsymbol{V_{CE}}_{(\text{sat})}$, $\boldsymbol{V_{BE}}_{(\text{sat})}$ and the frequency $\boldsymbol{f}$ at which it is expected to oscillate. The value of $\boldsymbol{R_C}$ is calculated as:

$$R_C = \frac{V_{CC} - V_{CE(sat)}}{I_{C(sat)}}$$ -- 3.103

$\boldsymbol{I_{B(\min)}}$ is now calculated as:

$$I_{B(\min)} = \frac{I_{C(sat)}}{h_{FE(min)}}$$ --- 3.104

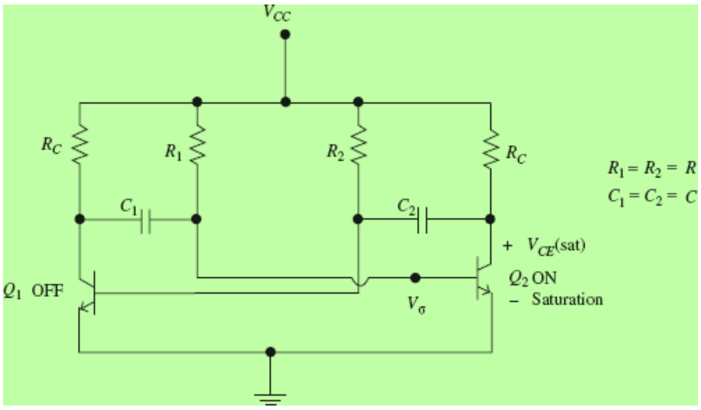

Figure 3.36 The design of an astable multivibrator

Now select:

$$I_{B(\text{sat})} = 1.5\, I_{B(\min)}$$ --- 3.105

to ensure that the ON device is really in saturation:

$$R = \frac{V_{CC} - V_\sigma}{I_{B(sat)}}$$ -- 3.106

For the ON device to be in saturation, $R \leq h_{FE}R_C$ needs to be satisfied.

For a symmetric astable multivibrator, $\boldsymbol{f} = 0.7/\boldsymbol{RC}$.

Using this relation, the value of $\boldsymbol{C}$ can be fixed. Example 3.7 further elucidates the point.

EXAMPLE PROBLEM

Example 3.7: Design an astable multivibrator, assuming that silicon devices with $\boldsymbol{h_{FE(\min)}} = 40$ are used. Also assume that $\boldsymbol{V_{CC}} = 10$ V, $\boldsymbol{I_{C(\text{sat})}} = 5$ mA. Let the desired frequency of oscillations be 5 kHz. For transistor used, $\boldsymbol{V_{CE(\text{sat})}} = 0.2$ V, $\boldsymbol{V_{BE(\text{sat})}} = \boldsymbol{V_\sigma} = 0.7$ V.

Solution:

$$R_c = \frac{V_{CC} - V_{CE(\text{sat})}}{I_{C(\text{sat})}} = \frac{10 - 0.2 \text{ V}}{5 \text{ mA}} = \frac{9.8}{5 \text{ mA}} = 1.96 \text{ k}\Omega$$

Select $R_C = 2$ kΩ

$$I_{B\ (\text{min})} = \frac{I_{C(\text{sat})}}{h_{FE\ (\text{min})}} = \frac{5 \text{ mA}}{40} = 0.125 \text{ mA}$$

Select $I_{B(\text{sat})} = 1.5I_B(\text{min}) = 1.5 \times 0.125 = 0.187$ mA

$$\therefore R = \frac{V_{CC} - V_{\sigma}}{I_{B(\text{sat})}} = \frac{10 - 0.7}{0.187 \text{ mA}} = \frac{9.3}{0.187 \text{ mA}} = 49.7 \text{ k}\Omega$$

Select $R = 47$ kΩ

For the ON transistor to be in saturation, the condition is $R \leq h_{FE}R_C$. Verify whether $R \leq h_{FE}R_C$ or not.

$$h_{FE}R_C = 40 \times 2 \text{ k}\Omega = 80 \text{ k}\Omega$$

$R < h_{FE}R_C$, hence, Q_2 is in saturation.

$f = \dfrac{0.7}{RC}$, for a symmetric astable multivibrator.

We have $f = 5$ kHz

$$5 \times 10^3 = \frac{0.7}{47 \times 10^3 \times C}$$

$$C = \frac{0.7}{5 \times 47 \times 10^{-6}} = 0.003\ \mu\text{F}$$

Alternately, if this were to be an un-symmetric astable multivibrator ($T_1 \neq T_2$), then the duty cycle (= $T_1/(T_1 + T_2) = T_1/T$) will have to be specified to fix the component values of R_1, R_2, C_1 and C_2. That is, let $R_1 = R_2 = R$ and duty cycle be specified as 40 per cent. If $f = 5$ kHz, then

$T = T_1 + T_2 = 0.2$ ms

$T_1/(T_1 + T_2) = T_1/T = 0.4$ ms

Hence, $T_1 = (0.4)(0.2) = 0.08$ ms, $T_2 = 0.2 - 0.08 = 0.12$ ms.

From Eq. (3.99) we know that:

$\boldsymbol{T}_2 = 0.69\ \boldsymbol{\tau}_1 = 0.69\ \boldsymbol{RC}_1 = (0.69)(47\text{k}\Omega)\boldsymbol{C}_1 = 0.08$ ms

Hence,

$$C_1 = \frac{0.08 \times 10^{-3}}{0.69 \times 47 \times 10^3} = 2.47 \text{ nF.}$$

Similarly,

$$T_1 = 0.69\ \tau_2 = 0.69RC_2 = (0.69)(47\text{k}\Omega)C_2 = 0.12 \text{ ms}$$

$$C_2 = \frac{0.12 \times 10^{-3}}{0.69 \times 47 \times 10^3} = 3.7 \text{ nF}$$

3.8.3 An Astable Multivibrator as a Voltage-Controlled Oscillator:

A voltage-controlled oscillator (VCO) is one in which the frequency of oscillations varies as a function of voltage. The same circuit is also called a voltage-to-frequency converter (VFC) because a given voltage gives rise to a specific frequency. An astable multivibrator is used as voltage-controlled oscillator [see Figure 3.37(a)]. A comparison of this with the circuit shown in Figure 3.33. shows that here the two resistors $\boldsymbol{R}$ and $\boldsymbol{R}$ are returned to a separate source $\boldsymbol{V_{BB}}$ rather than to $\boldsymbol{V_{CC}}$.

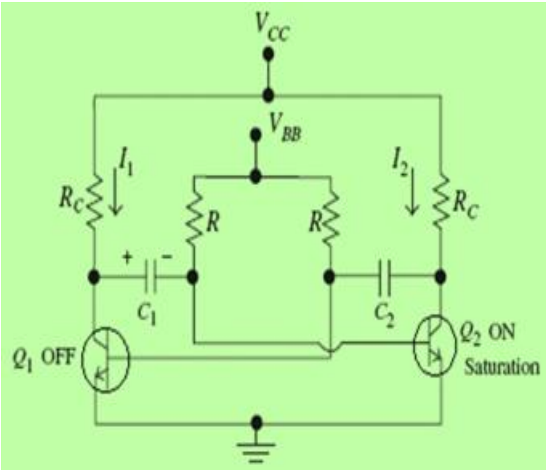

FIGURE 3.37(a) A voltage-to-frequency converter

When $\boldsymbol{Q_1}$ is OFF and $\boldsymbol{Q_2}$ is ON, $\boldsymbol{C_1}$ charges. When $\boldsymbol{Q_1}$ is ON, the charge on $\boldsymbol{C_1}$ decays with a time constant $\boldsymbol{\tau_1} = \boldsymbol{RC_1}$ as shown in Figure 3.37(b). As a result, the voltage at the base of $\boldsymbol{Q_2}$, $\boldsymbol{V_{B2}}$ varies with time, [see Figure 3.37(c)].

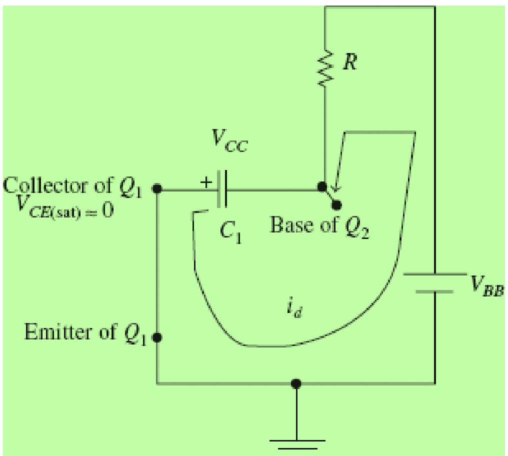

Figure 3.37(b) The discharge of condenser C_1 through R

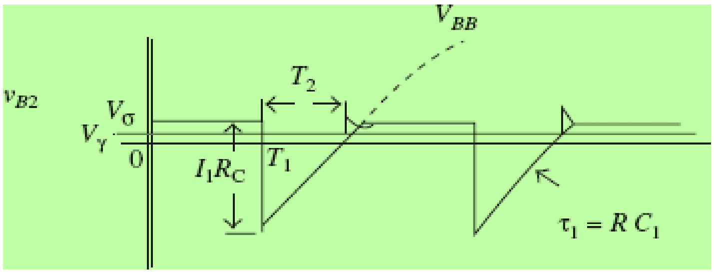

Figure 3.37(c) The voltage variation at the base of Q_2

We know from Eq. (3.93),

$v_{B2}(t) \;=\; v_f - (v_f - v_i)\, e^{-t/\tau_1}$ ---3.107

Here $v_f = V_{BB}$, $v_i = \; V_\sigma - I_1 R_C \;=\; V_\sigma - V_{CC} + V_{CE(sat)}$

Since $I_1 R_C \;=\; V_{CC} - V_{CE(sat)}$

Substituting these values in the Eq. (3.107), we get

$$v_{B2}(t) \;=\; V_{BB} - (V_{BB} - V_\sigma + V_{CC} - V_{CE(sat)})\, e^{-t/\tau_1}$$

At $t = T_2$, $v_{B2}(t) \;=\; V_\gamma$

$$\therefore V_\gamma \;=\; V_{BB} - (V_{BB} - V_\sigma + V_{CC} - V_{CE(sat)})\, e^{-T_2/\tau_1}$$

If the junction voltages are small,

$$\therefore 0 \;=\; V_{BB} - (V_{BB} - 0 + V_{CC} - 0)\, e^{-T_2/\tau_1}$$

For a symmetric circuit, $T_1 = T_2 = \frac{T}{2}$ $\;and\;$ $\tau_1 = \tau_2 = \tau$

$T_1 = T_2 = \frac{T}{2} = \;\tau\; ln\frac{V_{BB}+V_{CC}}{V_{BB}}$---3.108

Consequently, for a symmetric astable multivibrator:

$T = 2\;\tau\; ln\frac{V_{BB}+V_{CC}}{V_{BB}} \;=\; 2\;\tau\; ln\left(1+\frac{V_{CC}}{V_{BB}}\right)$--3.109

And, frequency $f = \frac{1}{T} = \frac{1}{2\;\tau\;\; ln\left(1+\frac{V_{CC}}{V_{BB}}\right)}$ --3.110

As the frequency of the multivibrator can be varied by simply varying V_{BB}, this circuit is called a voltage-controlled oscillator or voltage-to-frequency converter.