Oscillator

Dr. A. Balamurugan

Objectives

- Describe the basic concept of an oscillator
- Discuss the basic principles of operation of an oscillator
- Analyze the operation of RC and LC oscillators
- Describe the operation of the basic relaxation oscillator circuits

Introduction

- Oscillator is an electronic circuit that generates a periodic waveform on its output without an external signal source. It is used to convert dc to ac.
- Oscillators are circuits that produce a continuous signal of some type without the need of an input.
- These signals serve a variety of purposes.
- Communications systems, digital systems (including computers), and test equipment make use of oscillators

Oscillators

Oscillation: an effect that repeatedly and regularly fluctuates about the mean value

Oscillator: circuit that produces oscillation

Characteristics: wave-shape, frequency, amplitude, distortion, stability

Application of Oscillators

- **Oscillators are used to generate signals, e.g.**
  - Used as a local oscillator to transform the RF signals to IF signals in a receiver;
  - Used to generate RF carrier in a transmitter
  - Used to generate clocks in digital systems;
  - Used as sweep circuits in TV sets and CRO.

Oscillators

- Oscillators are circuits that generate periodic signals
- An oscillator converts DC power from the power supply into AC signal power spontaneously - without the need for an AC input source

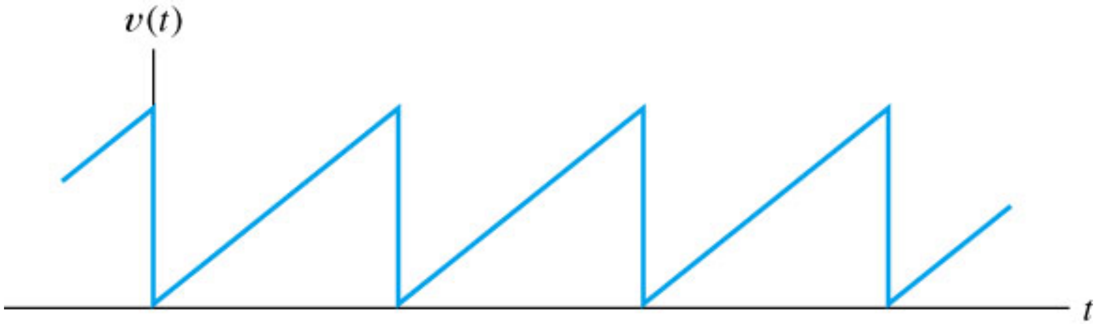
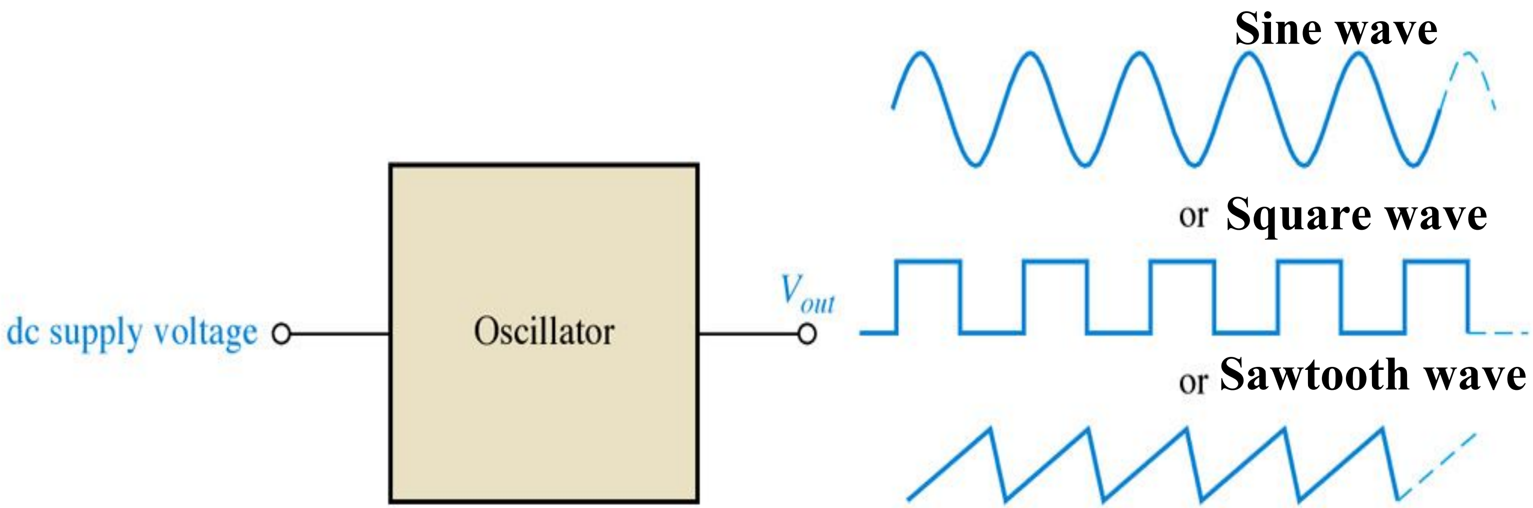


Figure 9.67 Repetitive ramp waveform.

Introduction

- An oscillator is a circuit that produces a repetitive signal from a dc voltage.
- The feedback oscillator **relies on a positive feedback** of the output to **maintain the oscillations**.
- The relaxation oscillator makes use of an RC timing circuit to generate a nonsinusoidal signal such as square wave

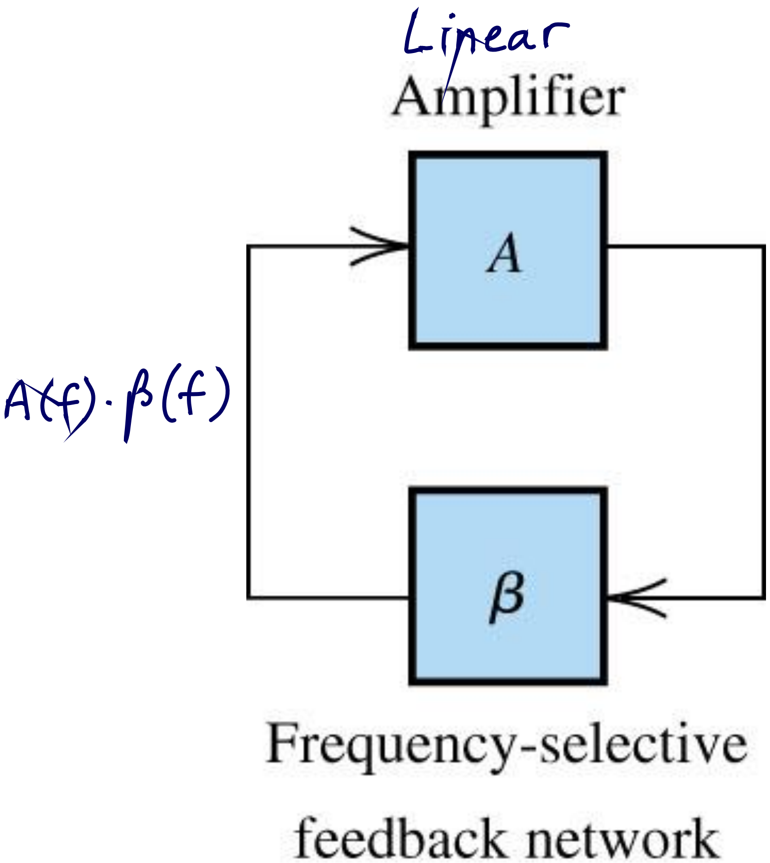


Types of oscillators

1. **RC oscillators**
   - Wien Bridge
   - Phase-Shift
2. **LC oscillators**
   - Hartley
   - Colpitts
   - Crystal
3. **Unijunction / relaxation oscillators**

Linear Oscillators

Linear oscillators produces an approximately sinusoidal output



Switching Oscillators:
another approach to oscillator design
It employs active devices as switches rather than linear amplifiers.

Figure 9.68 A linear oscillator is formed by connecting an amplifier and
a feedback network in a loop.

Integrant of Linear Oscillators

For sinusoidal input is connected
"Linear" because the output is approximately sinusoidal

A linear oscillator contains:
- a frequency selection feedback network
- an amplifier to maintain the loop gain at **unity**

Basic Linear Oscillator

$$V_o = AV_\varepsilon = A(V_s + V_f) \quad \text{and} \quad V_f = \beta V_o$$

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

If $V_s = 0$, the only way that V_o can be nonzero is that loop gain $A\beta$=1 which implies that

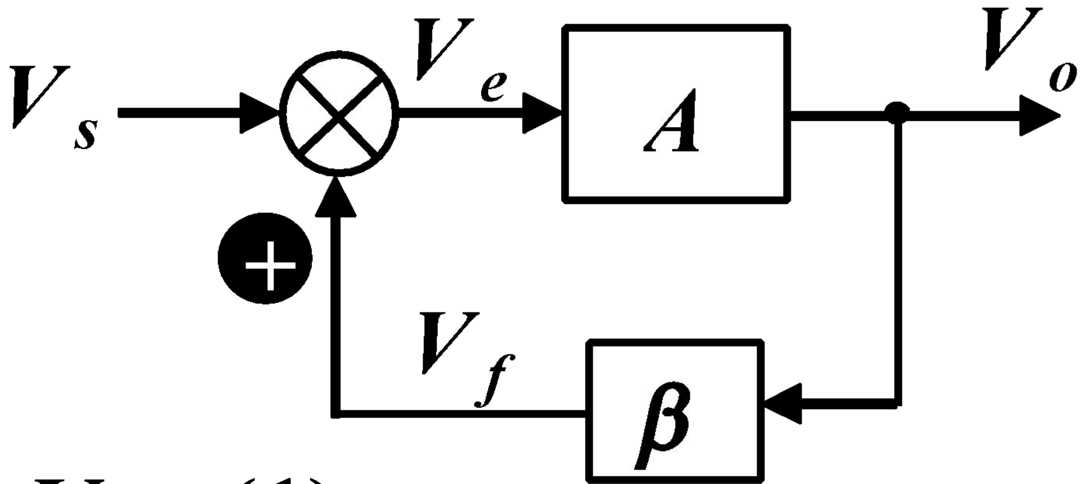
$$|A\beta| = 1$$

$$\angle A\beta = 0$$

(Barkhausen Criterion)

Basic principles for oscillation

- An oscillator is an amplifier with positive feedback.



$$V_e = V_s + V_f \quad (1)$$

$$V_f = \beta V_o \quad (2)$$

$$V_o = AV_e = A\left(V_s + V_f\right) = A\left(V_s + \beta V_o\right) \quad (3)$$

Basic principles for oscillation

$$V_o = AV_e$$

$$= A\left(V_s + V_f\right) = A\left(V_s + \beta V_o\right)$$

$$V_o = AV_s + A\beta V_o$$

$$\left(1 - A\beta\right)V_o = AV_s$$

- The closed loop gain is:

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{\left(1 - A\beta\right)}$$

Basic principles for oscillation

- In general A and β are functions of frequency and thus may be written as;

$$A_f(s) = \frac{V_o}{V_s}(s) = \frac{A(s)}{1 - A(s)\beta(s)}$$

$A(s)\beta(s)$ is known as **loop gain**

Basic principles for oscillation

- Writing $T(s) = A(s)\beta(s)$ the loop gain becomes;

$$A_f(s) = \frac{A(s)}{1 - T(s)}$$

- Replacing s with $j\omega$

$$A_f(j\omega) = \frac{A(j\omega)}{1 - T(j\omega)}$$

- and $T(j\omega) = A(j\omega)\beta(j\omega)$

Basic principles for oscillation

- At a specific frequency f_0

$$T(j\omega_0) = A(j\omega_0)\beta(j\omega_0) = 1$$

- At this frequency, the closed loop gain;

$$A_f(j\omega_0) = \frac{A(j\omega_0)}{1 - A(j\omega_0)\beta(j\omega_0)}$$

will be infinite, i.e. the circuit will have finite output for zero input signal - oscillation

Basic principles for oscillation

- Thus, the condition for sinusoidal oscillation of frequency f_0 is;

$$A(j\omega_0)\beta(j\omega_0) = 1$$

- This is known as **Barkhausen criterion**.
- The frequency of oscillation is solely determined by the phase characteristic of the feedback loop – the loop oscillates at the frequency for which the phase is zero.

Barkhausen Criterion – another way

What are the requirements for oscillation ?

$$\dot{X}_{out} = \frac{A(f)}{1 - A(f)\beta(f)}\dot{X}_s$$

If $\dot{X}_s$ is zero, the only way $\dot{X}_{out}$ can be non zero is for the denominator to be zero → BARKHAUSEN CRIT.

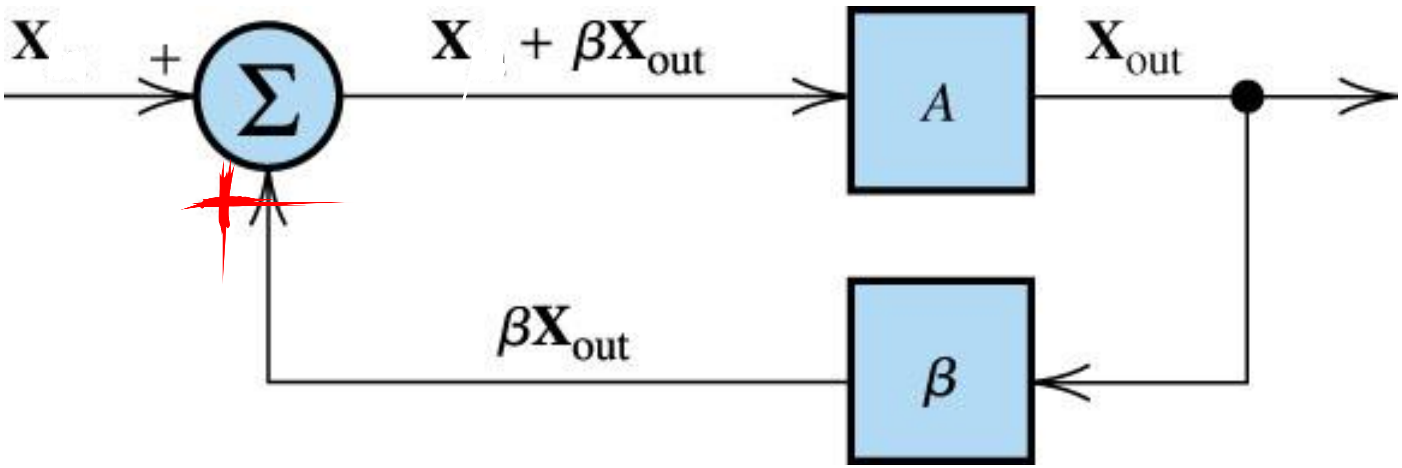


Figure 9.69 Linear oscillator with external signal X_{in} injected.

Barkhausen Criterion

$$A(f)\cdot\beta(f)=1$$ ← BARKHAUSEN CRITERION

⇕

1. The phase angle of the loop gain $A(f)\beta(f)$ must be zero at the frequency of oscillation
2. The magnitude of the loop gain must be unity

⇕

1. The real part of $A(f)\cdot\beta(f)$ must be unity
2. The imaginary part of $A(f)\cdot\beta(f)$ must be zero

How does the oscillation get started?

- Noise signals and the transients associated with the circuit turning on provide the initial source signal that initiate the oscillation

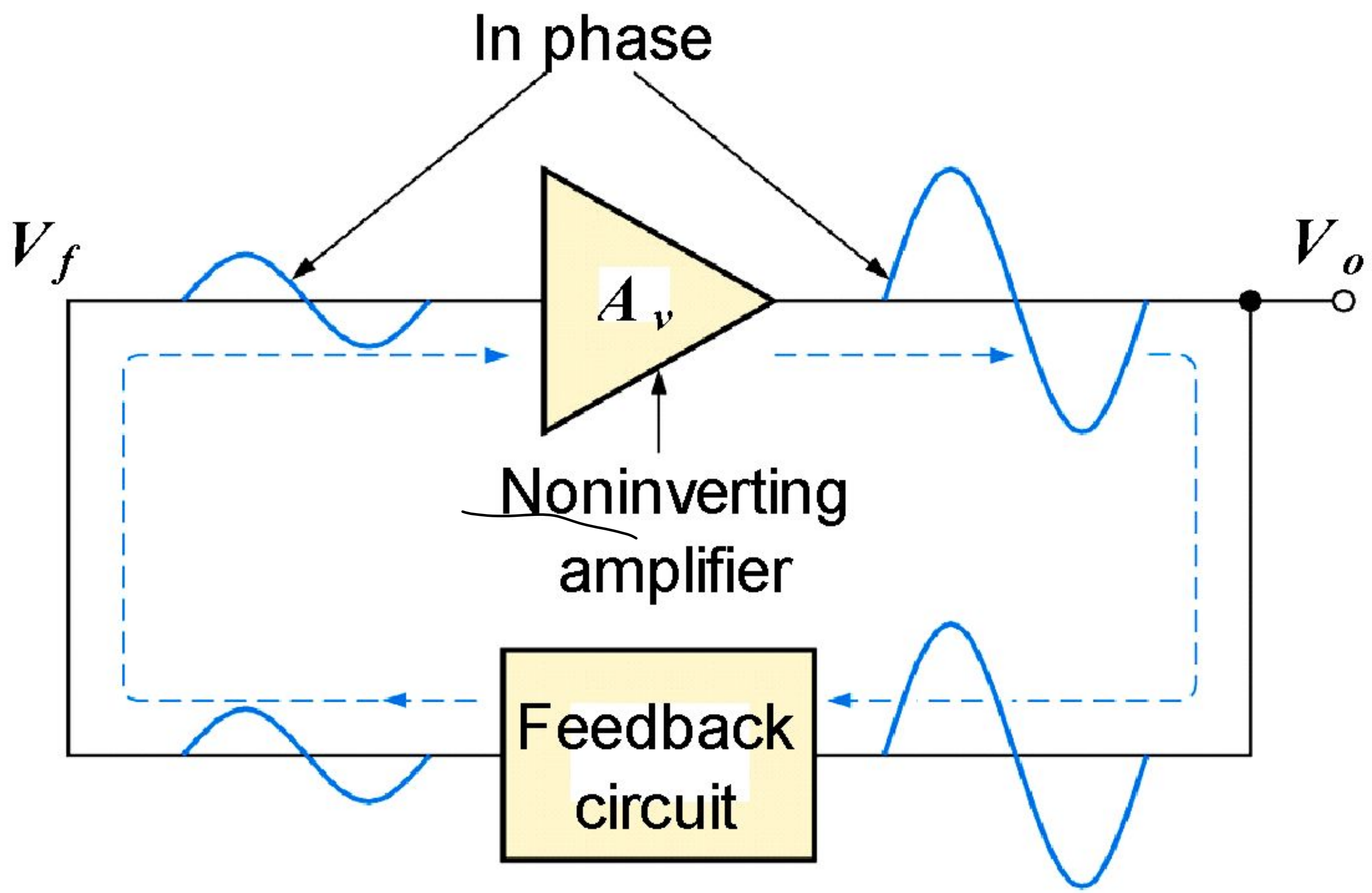
Practical Design Considerations

- Usually, oscillators are designed so that the loop gain magnitude is slightly higher than unity at the desired frequency of oscillation
- This is done because if we designed for unity loop gain magnitude a slight reduction in gain would result in oscillations that die to zero
- The drawback is that the oscillation will be slightly distorted (the higher gain results in oscillation that grows up to the point that will be clipped)

Basic principles for oscillation

- The feedback oscillator is widely used for generation of sine wave signals.
- The positive (in phase) feedback arrangement maintains the oscillations.
- The feedback gain must be kept to unity to keep the output from distorting.

Basic principles for oscillation



Design Criteria for Oscillators

1. The magnitude of the loop gain must be unity or slightly larger

   $$|A\beta| = 1$$ Barkhaussen criterion

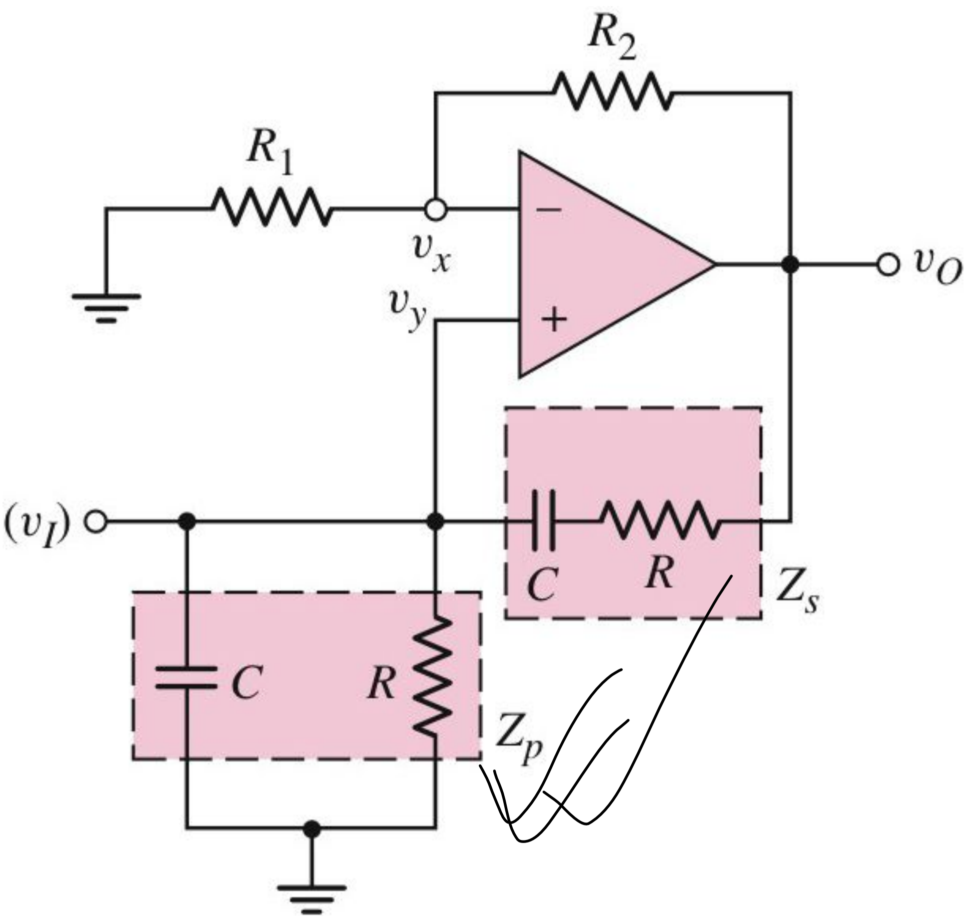
2. Total phase shift, φ of the loop gain mus t be Nx360° where N=0, 1, 2, …

RC Oscillators

- RC feedback oscillators are generally limited to frequencies of 1 MHz or less.
- The types of RC oscillators that we will discuss are the **Wien-bridge** and the **phase-shift**

Wien-bridge Oscillator

- It is a low frequency oscillator which ranges from a few kHz to 1 MHz.



Another way

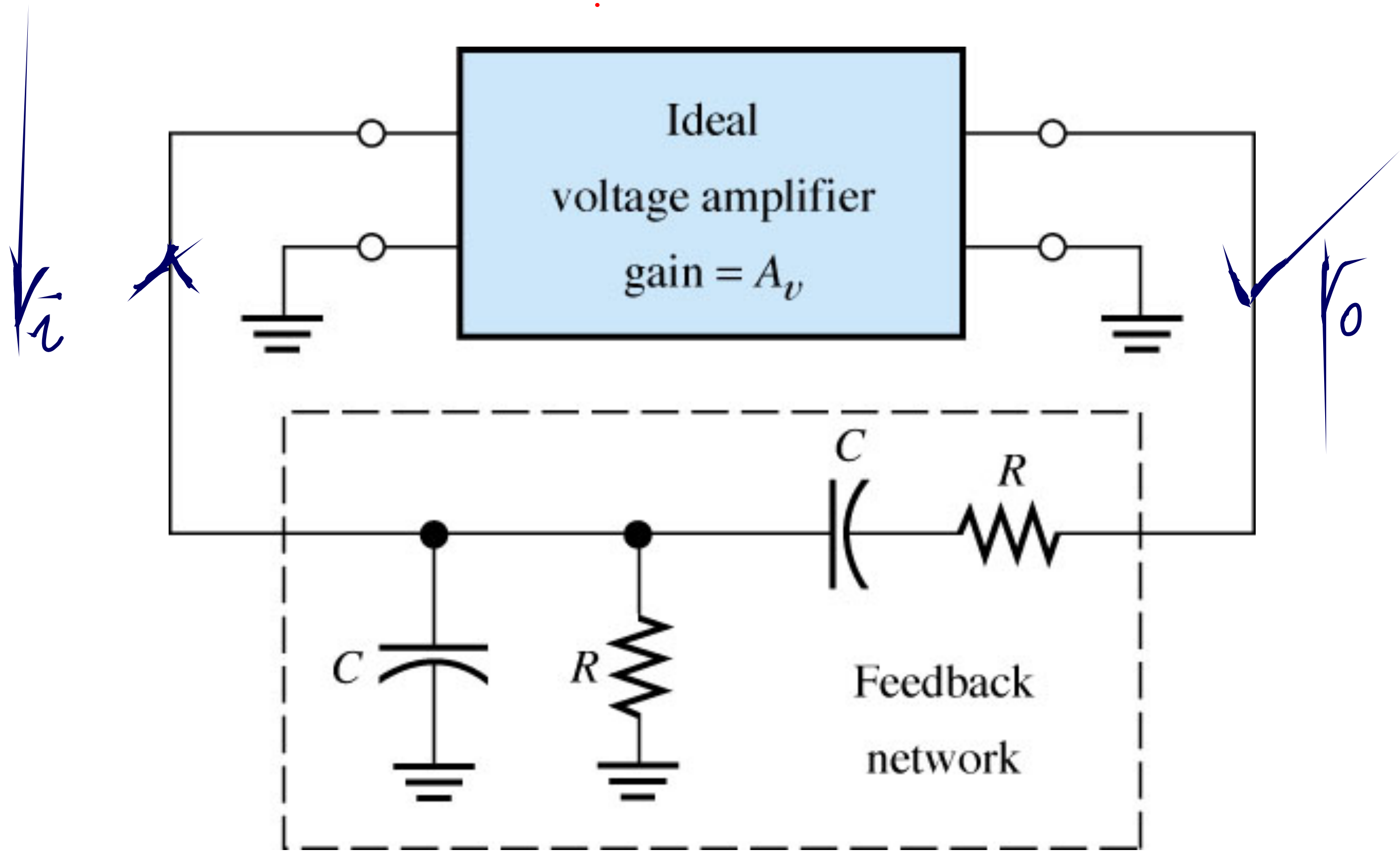


Figure 9.70 Typical linear oscillator.

Wien-bridge Oscillator

- The loop gain for the oscillator is;

$$T(s) = A(s)\beta(s) = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{Z_p}{Z_p + Z_s}\right)$$

- where;

$$Z_p = \frac{R}{1 + sRC}$$

- and;

$$Z_s = \frac{1 + sRC}{sC}$$

Wien-bridge Oscillator

- Hence;

$$T(s)=\left(1+\frac{R_2}{R_1}\right)\left[\frac{1}{3+sRC+(1/sRC)}\right]$$

- Substituting for s;

$$T(j\omega)=\left(1+\frac{R_2}{R_1}\right)\left[\frac{1}{3+j\omega RC+(1/j\omega RC)}\right]$$

- For oscillation frequency f_0 $\approx[\omega_0]$

$$T(j\omega_0)=\left(1+\frac{R_2}{R_1}\right)\left[\frac{1}{3+j\omega_0 RC+(1/j\omega_0 RC)}\right]$$

Wien-bridge Oscillator

- Since at the frequency of oscillation, $T(j\omega)$ must be real (for zero phase condition), the imaginary component must be zero;

$$j\omega_0 RC + \frac{1}{j\omega_0 RC} = 0$$

- which gives us – [how?! – do it now]

$$\omega_0 = \frac{1}{RC}$$

$$j\omega_0 RC + \frac{1}{j\omega_0 RC} = 0$$

$$==> j\omega_0 RC = -\frac{1}{j\omega_0 RC}$$

$$==> (j\omega_0 RC)^2 = -1$$

$$==> j^2(\omega_0 RC)^2 = -1$$

$$==> -1.(\omega_0 RC)^2 = -1$$

$$==> (\omega_0 RC)^2 = 1$$

$$==> \omega_0 RC = 1$$

$$==> \omega_0 = \frac{1}{RC}$$

Wien-bridge Oscillator

- From the previous eq. (for oscillation frequency f_0),

$$T(j\omega_0) = \left(1 + \frac{R_2}{R_1}\right)\left[\frac{1}{3 + j\omega_0 RC + (1/j\omega_0 RC)}\right]$$

- the magnitude condition is;

$$1 = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{3+0}\right) = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{3}\right) \qquad \Rightarrow \frac{R_2}{R_1} = 3 - 1 = 2$$

To ensure oscillation, the ratio R_2/R_1 must be slightly greater than 2.

Wien-bridge Oscillator

- With the ratio;

$$\frac{R_2}{R_1} = 2$$

- then;

$$K \equiv 1 + \frac{R_2}{R_1} = 3$$

$K = 3$ ensures the loop gain of unity – oscillation

- $K > 3$: growing oscillations
- $K < 3$: decreasing oscillations

Wien-Bridge Oscillator – another way

$$\frac{R_2}{R_1} = 2$$

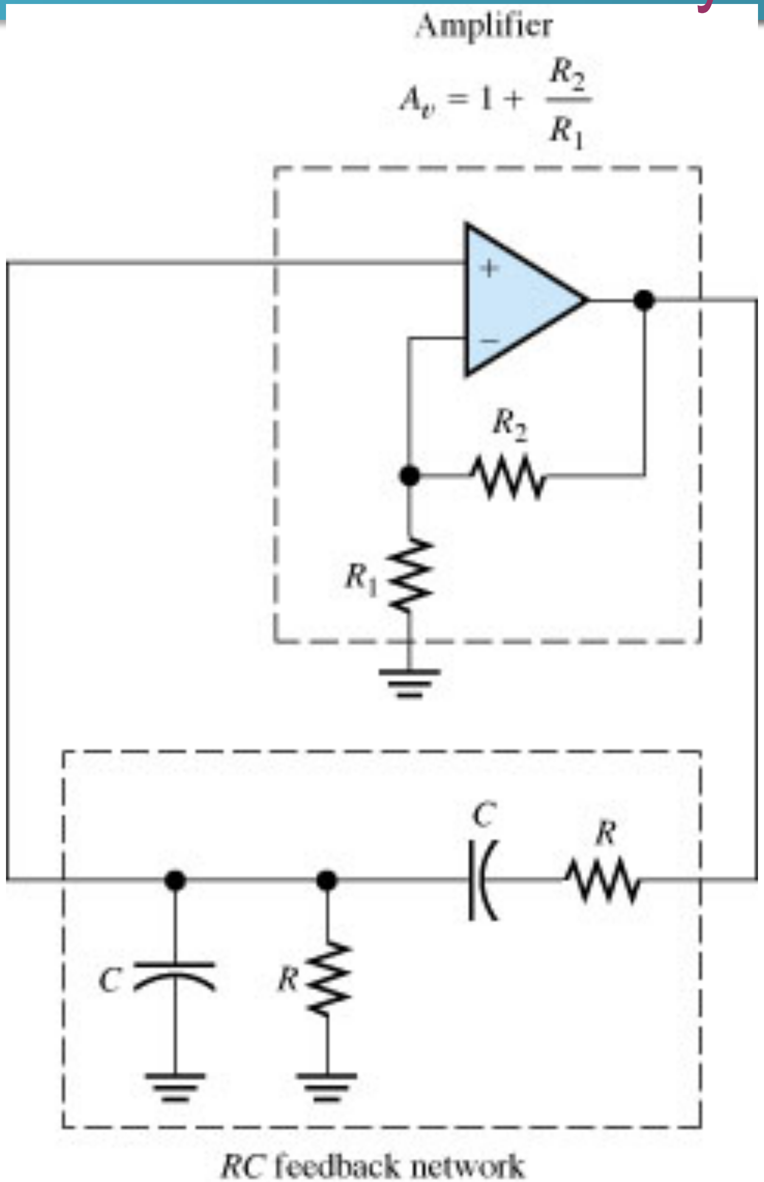
$$\Rightarrow R_2 = 2R_1$$

$Av_{min} = 3 \rightarrow R_2 \geq 2R_1$

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

$$non-inverting,$$

$$gain = A = 1 + \frac{R_2}{R_1} = 1 + 2 = 3$$



Wien-bridge oscillator.

Wien-Bridge oscillator output

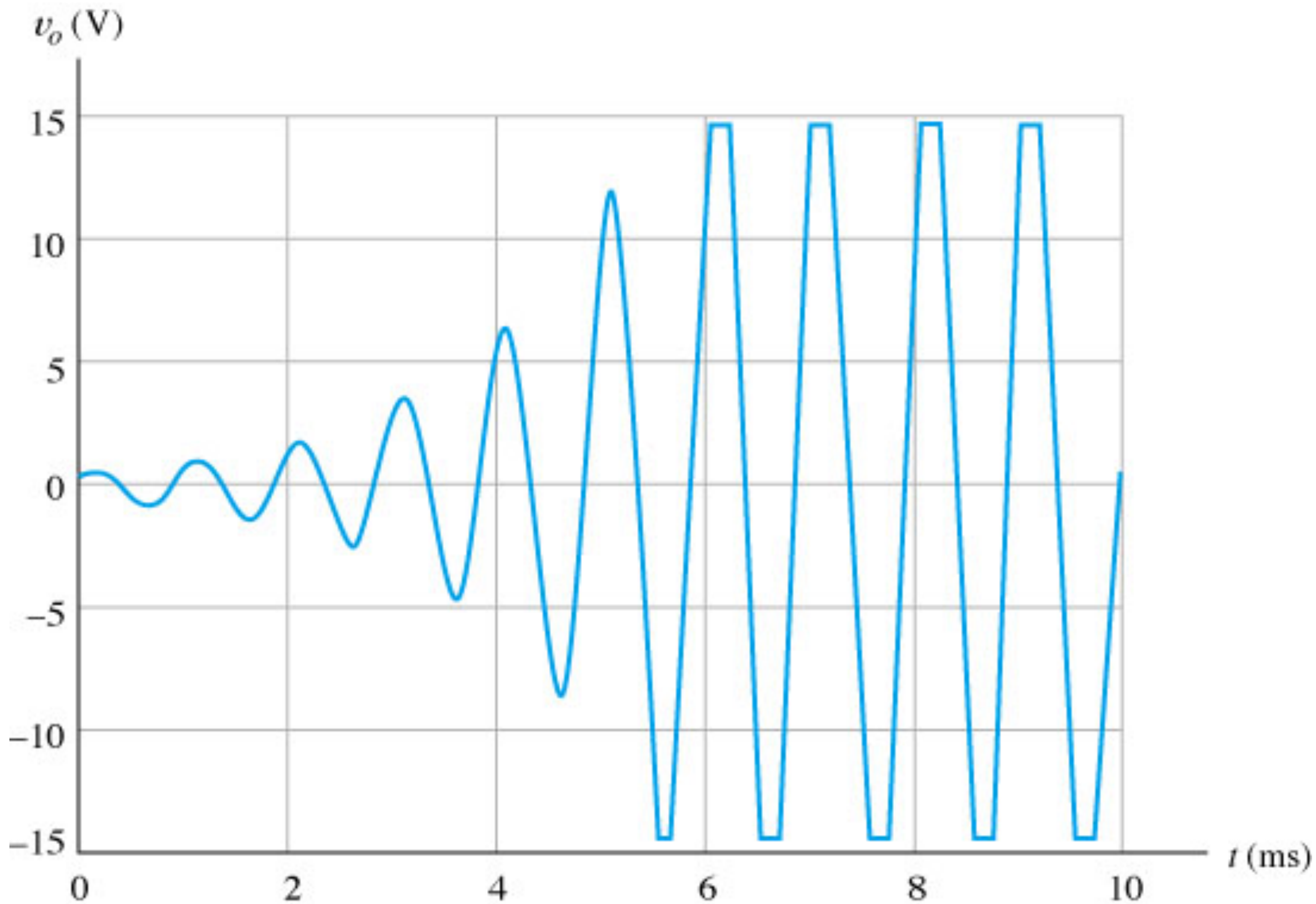


Figure 9.75 Example of output voltage of the oscillator.

Wien Bridge Oscillator

Frequency Selection Network

Let $X_{C1} = \dfrac{1}{\omega C_1}$ and $X_{C2} = \dfrac{1}{\omega C_2}$

$$Z_1 = R_1 - jX_{C1}$$

$$Z_2 = \left[\frac{1}{R_2} + \frac{1}{-jX_{C2}} \right]^{-1} = \frac{-jR_2 X_{C2}}{R_2 - jX_{C2}}$$

Therefore, the feedback factor,

$$\beta = \frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2} = \frac{(-jR_2 X_{C2} / R_2 - jX_{C2})}{(R_1 - jX_{C1}) + (-jR_2 X_{C2} / R_2 - jX_{C2})}$$

$$\beta = \frac{-jR_2 X_{C2}}{(R_1 - jX_{C1})(R_2 - jX_{C2}) - jR_2 X_{C2}}$$

β can be rewritten as:

$$\beta = \frac{R_2 X_{C2}}{R_1 X_{C2} + R_2 X_{C1} + R_2 X_{C2} + j(R_1 R_2 - X_{C1} X_{C2})}$$

For ***Barkhausen Criterion***, imaginary part = 0, i.e.,

$$R_1 R_2 - X_{C1} X_{C2} = 0$$

$$\text{or} \quad R_1 R_2 = \frac{1}{\omega C_1} \frac{1}{\omega C_2}$$

$$\Rightarrow \omega = 1 / \sqrt{R_1 R_2 C_1 C_2}$$

Supposing,

R_1=R_2=R and X_{C1}= X_{C2}=X_C,

$$\beta = \frac{R X_C}{3 R X_C + j(R^2 - X_C^2)}$$

Example

By setting $\omega = \dfrac{1}{RC}$, we get

Imaginary part = 0 and

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

Due to ***Barkhausen Criterion***,

Loop gain $A_v\beta$=1

where

A_v : Gain of the amplifier

$$A_v\beta = 1 \Rightarrow A_v = 3 = 1 + \frac{R_f}{R_1}$$

Therefore, $\dfrac{R_f}{R_1} = 2$

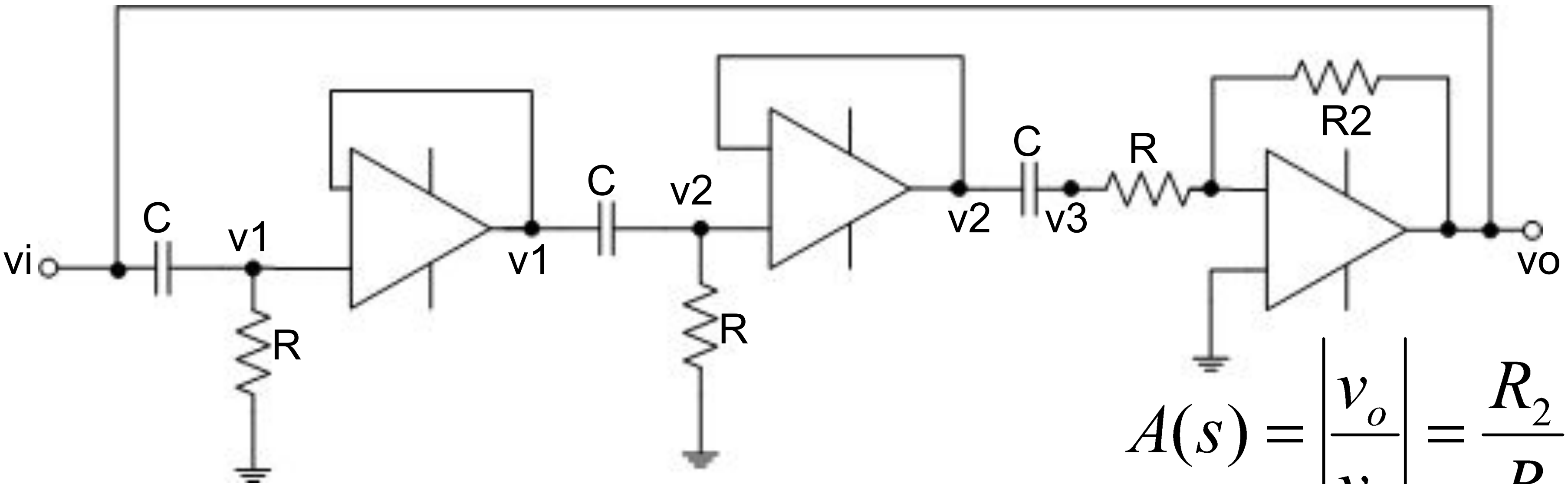
Wien Bridge Oscillator

Phase-Shift Oscillator

- The phase shift oscillator utilizes **three RC circuits to provide 180º phase shift** that when coupled with the 180º of the op-amp itself provides the necessary feedback to sustain oscillations.
- The **gain must be at least 29** to maintain the oscillations.
- The frequency of resonance for the this type is similar to any RC circuit oscillator:

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

Phase-Shift Oscillator



$$A(s) = \left|\frac{v_o}{v_3}\right| = \frac{R_2}{R}$$

$$v_1 = \left(\frac{sRC}{1+sRC}\right) v_i \qquad v_3 = \left(\frac{sRC}{1+sRC}\right)^3 v_i$$

$$v_2 = \left(\frac{sRC}{1+sRC}\right)^2 v_i \qquad \frac{v_3}{v_i} = \beta(s) = \left(\frac{sRC}{1+sRC}\right)^3$$

Phase-Shift Oscillator

- Loop gain, T(s):

$$T(s) = A(s)\beta(s) = \left(\frac{R_2}{R}\right)\left(\frac{sRC}{1+sRC}\right)^3$$

- Set s=jw

$$T(j\omega) = \left(\frac{R_2}{R}\right)\left(\frac{j\omega RC}{1+j\omega RC}\right)^3$$

$$T(j\omega) = -\left(\frac{R_2}{R}\right)\frac{(j\omega RC)(\omega RC)^2}{\left[1-3\omega^2R^2C^2\right]+j\omega RC\left[3-\omega^2R^2C^2\right]}$$

Phase-Shift Oscillator

- To satisfy condition $T(jw_o)=1$, real component must be zero since the numerator is purely imaginary.

$$1-3\omega^2R^2C^2=0$$

- the oscillation frequency:

$$\omega_0=\frac{1}{\sqrt{3}RC}$$

- Apply w_o in equation:

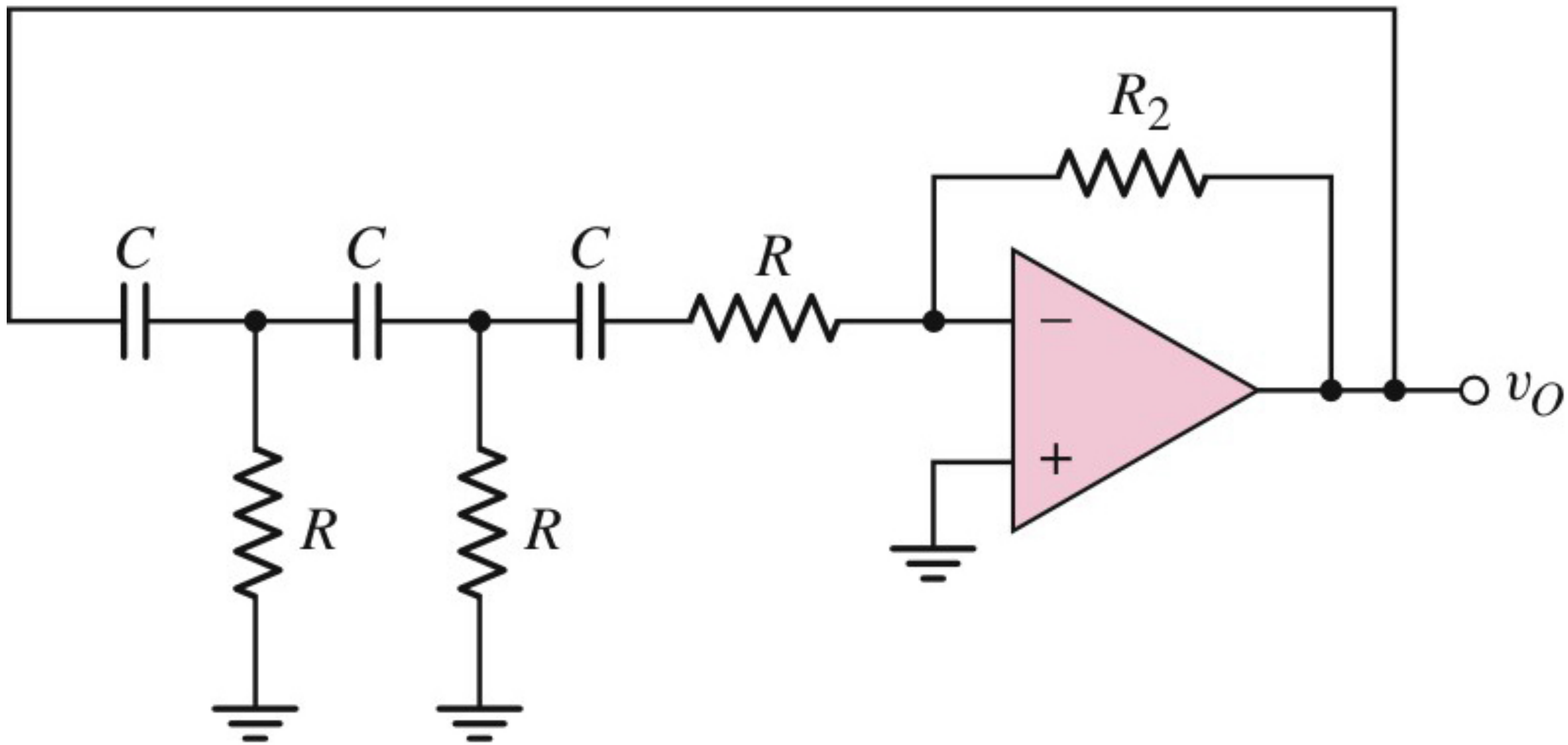
$$T(j\omega_o)=-\left(\frac{R_2}{R}\right)\frac{(j/\sqrt{3})(1/3)}{0+(j/\sqrt{3})\left[3-(1/3)\right]}=-\left(\frac{R_2}{R}\right)\left(\frac{1}{8}\right)$$

- To satisfy condition $T(jw_o)=1$

$$\frac{R_2}{R}=8$$

The gain greater than 8, the circuit will spontaneously begin oscillating & sustain oscillations

Phase-Shift Oscillator



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

$$\frac{R_2}{R} = 29$$

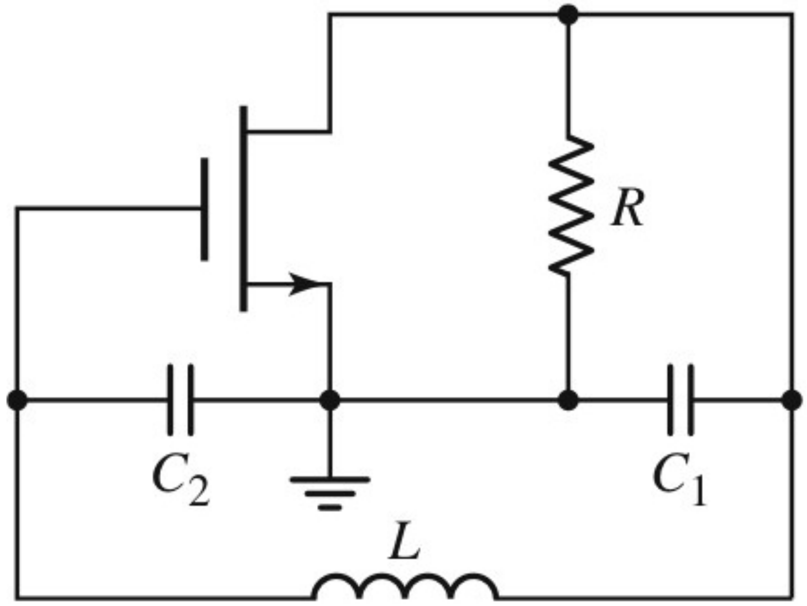
The gain must be at least 29 to maintain the oscillations

LC Oscillators

- Use transistors and LC tuned circuits or crystals in their feedback network.
- For hundreds of kHz to hundreds of MHz frequency range.
- Examine Colpitts, Hartley and crystal oscillator.

Colpitts Oscillator

- The Colpitts oscillator is a type of oscillator that uses an LC circuit in the feed-back loop.
- The feedback network is made up of a pair of *tapped capacitors (C_1 and C_2)* and *an inductor L* to produce a feedback necessary for oscillations.
- The output voltage is developed across C_1.
- The feedback voltage is developed across C_2.



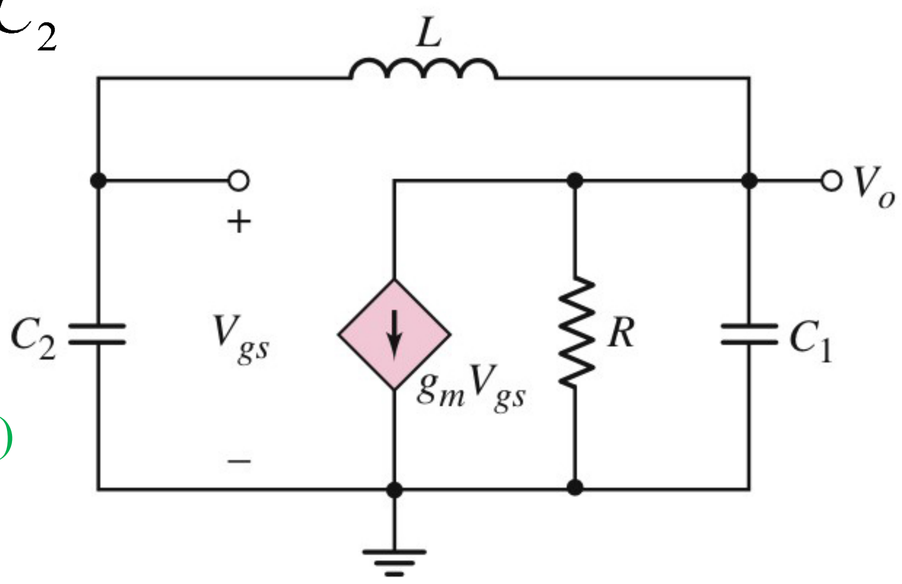
Colpitts Oscillator

- KCL at the output node:

$$\frac{V_o}{\frac{1}{sC_1}} + \frac{V_o}{R} + g_m V_{gs} + \frac{V_o}{sL + \frac{1}{sC_2}} = 0$$ - Eq (1)

- voltage divider produces:

$$V_{gs} = \left(\frac{\frac{1}{sC_2}}{\frac{1}{sC_2} + sL} \right) \bullet V_o$$ - Eq (2)



- substitute eq(2) into eq(1):

$$V_o \left[g_m + sC_2 + \left(1 + s^2 LC_2\right)\left(\frac{1}{R} + sC_1\right) \right] = 0$$

Colpitts Oscillator

- Assume that oscillation has started, then Vo≠0

$$s^3 LC_1C_2 + \frac{s^2 LC_2}{R} + s(C_1 + C_2) + \left(g_m + \frac{1}{R}\right) = 0$$

- Let s=jω

$$\left(g_m + \frac{1}{R} + \frac{\omega^2 LC_2}{R}\right) + j\omega\left[(C_1 + C_2) - \omega^2 LC_1C_2\right] = 0$$

- both real & imaginary component must be zero
  - Imaginary component:

$$\omega_o = \frac{1}{\sqrt{L\left(\frac{C_1C_2}{C_1 + C_2}\right)}}$$

- Eq (3)

Colpitts Oscillator

- both real & imaginary component must be zero
  - Imaginary component:

$$\frac{\omega^2 L C_2}{R} = g_m + \frac{1}{R} \quad \text{- Eq (4)}$$

- Combining Eq(3) and Eq(4):

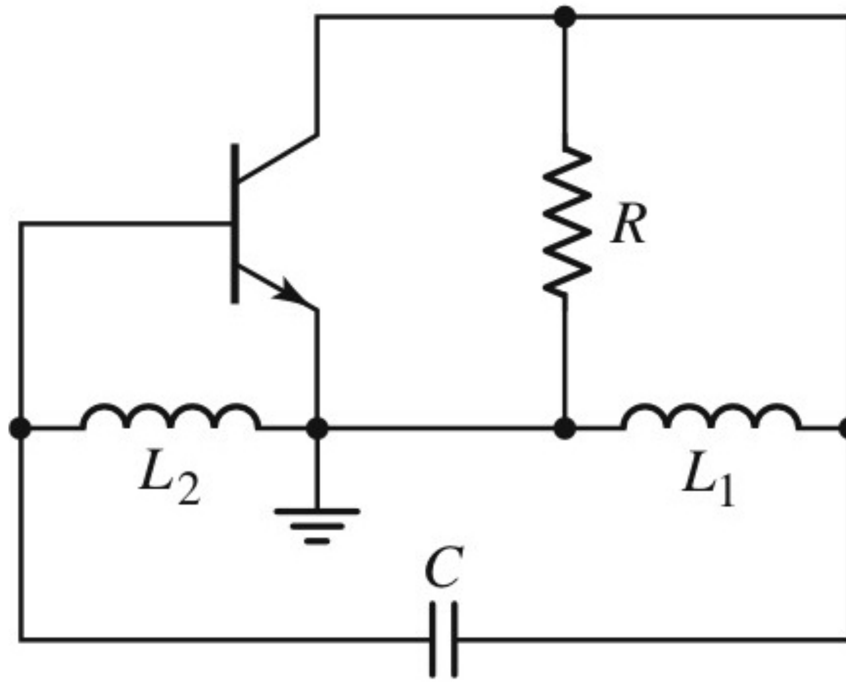
$$\frac{C_2}{C_1} = g_m R$$

- to initiate oscillations spontaneously:

$$g_m R > \left(\frac{C_2}{C_1} \right)$$

Hartley Oscillator

- The Hartley oscillator is almost identical to the Colpitts oscillator.
- The primary difference is that the feedback network of the Hartley oscillator uses *tapped inductors (L_1 and L_2)* and *a single capacitor C*.



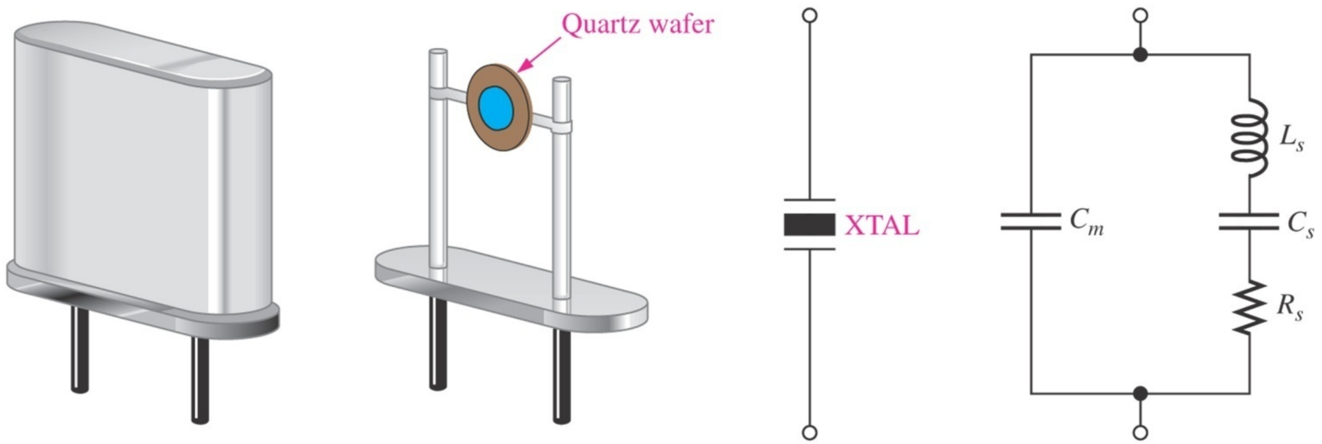
Hartley Oscillator

- the analysis of Hartley oscillator is identical to that Colpitts oscillator.
- the frequency of oscillation:

$$\omega_o = \frac{1}{\sqrt{(L_1 + L_2)C}}$$

Crystal Oscillator

- Most communications and digital applications require the use of oscillators with extremely stable output. Crystal oscillators are invented to overcome the output fluctuation experienced by conventional oscillators.
- Crystals used in electronic applications consist of a quartz wafer held between two metal plates and housed in a a package as shown in Fig. 9 (a) and (b).



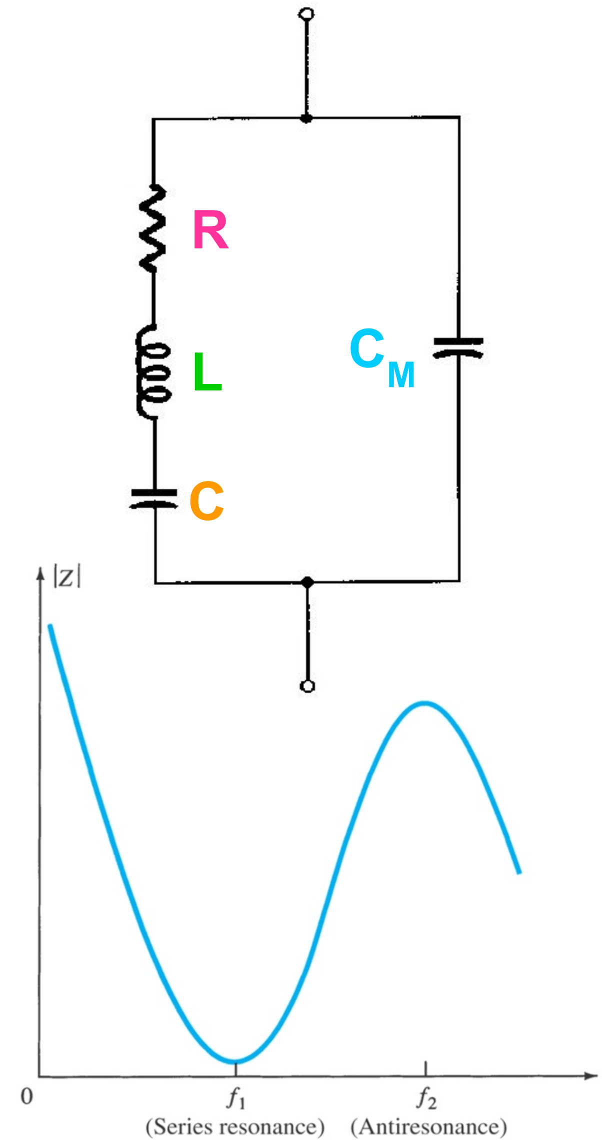
(a) Typical packaged crystal (b) Basic construction (without case) (c) Symbol (d) Electrical equivalent

Crystal Oscillator

- Piezoelectric Effect
  - The quartz crystal is made of silicon oxide (SiO_2) and exhibits a property called the *piezoelectric*
  - When a changing an alternating voltage is applied across the crystal, it vibrates at the frequency of the applied voltage. In the other word, the frequency of the applied ac voltage is equal to the natural resonant frequency of the crystal.
  - The thinner the crystal, higher its frequency of vibration. This phenomenon is called piezoelectric effect.

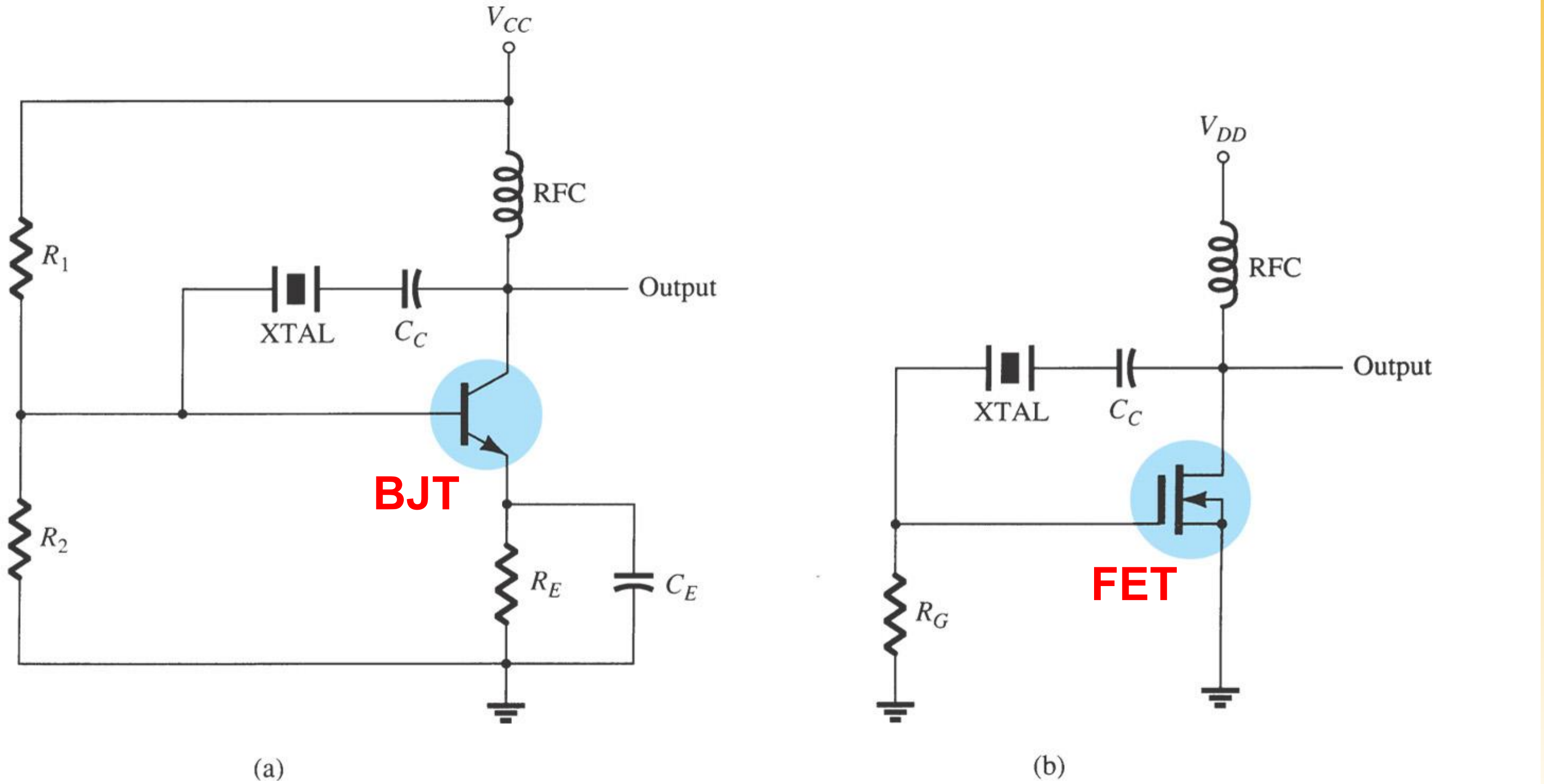
Crystal Oscillator

- Characteristic of Quartz Crystal
  - The crystal can have two resonant frequencies;
  - One is the series resonance frequency f_1 which occurs when $X_L = X_C$. At this frequency, crystal offers a very low impedance to the external circuit where $Z = R$.
  - The other is the parallel resonance (or antiresonance) frequency f_2 which occurs when reactance of the series leg equals the reactance of C_M. At this frequency, crystal offers a very high impedance to the external circuit



Crystal Oscillator

- The crystal is connected as a series element in the feedback path from collector to the base so that it is excited in the series-resonance mode



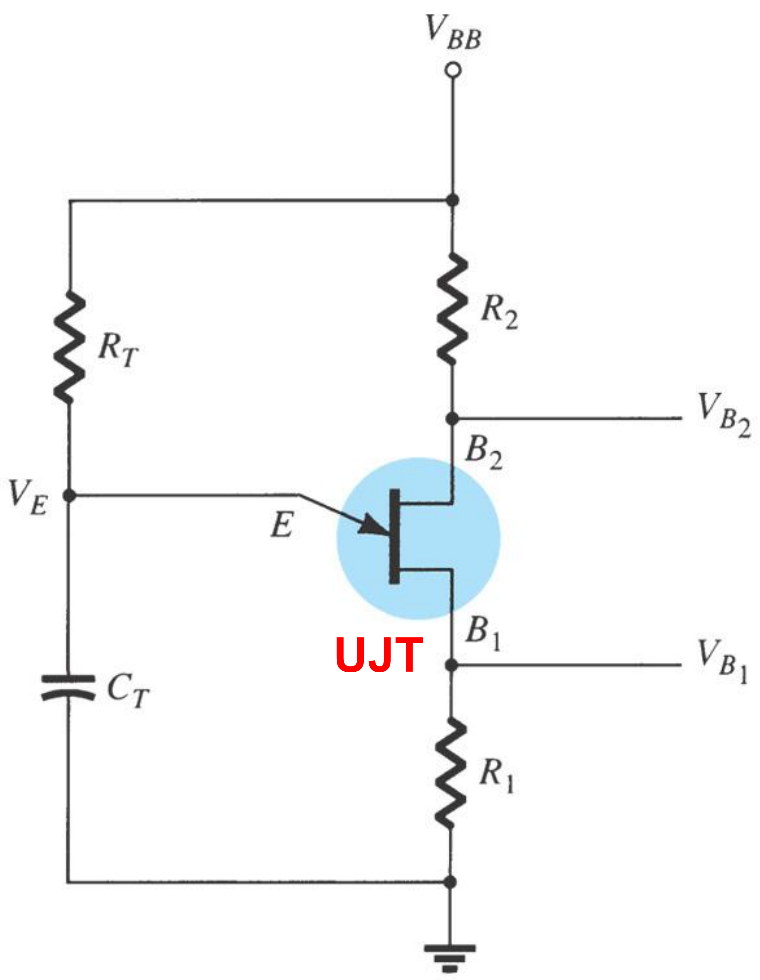
Crystal Oscillator

- Since, in series resonance, crystal impedance is the smallest that causes the crystal provides the largest positive feedback.
- Resistors R_1, R_2, and R_E provide a voltage-divider stabilized dc bias circuit. Capacitor C_E provides ac bypass of the emitter resistor, R_E to avoid degeneration.
- The RFC coil provides dc collector load and also prevents any ac signal from entering the dc supply.
- The coupling capacitor C_C has negligible reactance at circuit operating frequency but blocks any dc flow between collector and base.
- The oscillation frequency equals the series-resonance frequency of the crystal and is given by:

$$f_o = \frac{1}{2\pi\sqrt{LC_C}}$$

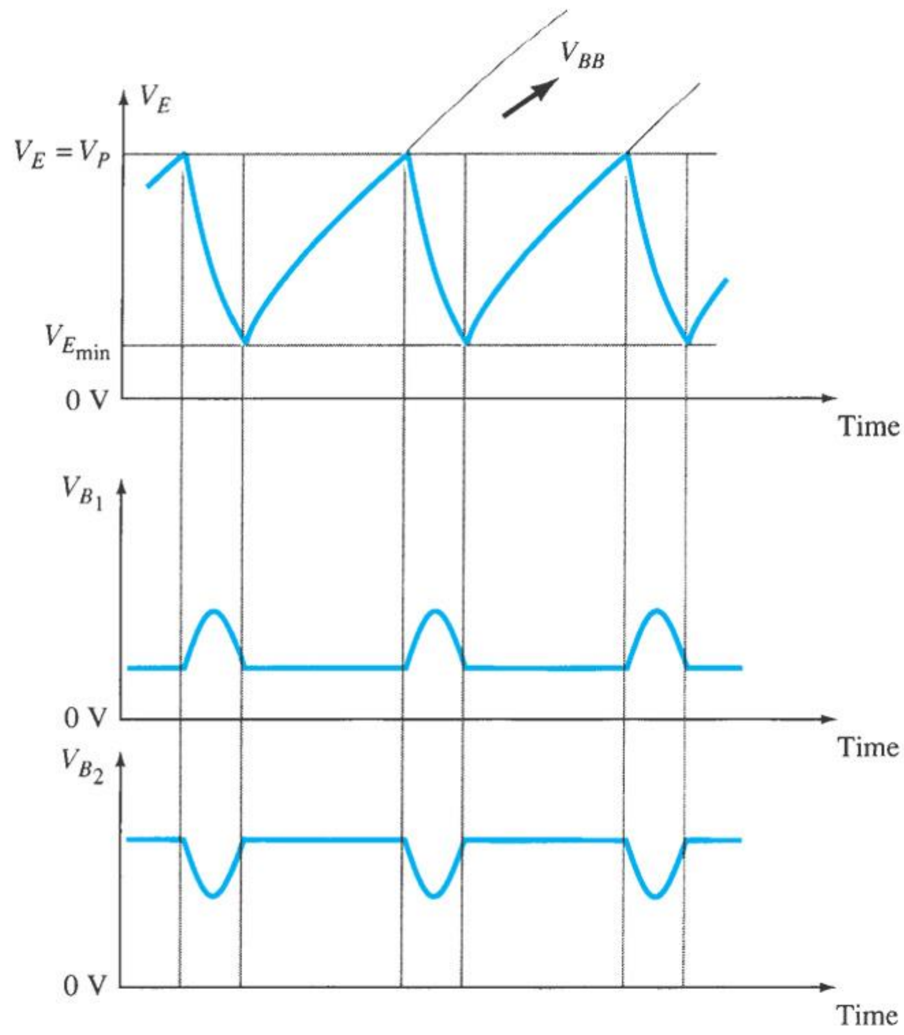
Unijunction Oscillator

- The unijunction transistor can be used in what is called a *relaxation oscillator* as shown by basic circuit as follow.
- The unijunction oscillator provides a pulse signal suitable for digital-circuit applications.
- Resistor R_T and capacitor C_T are the timing components that set the circuit oscillating rate



Unijunction Oscillator

- Sawtooth wave appears at the emitter of the transistor.
- This wave shows the gradual increase of capacitor voltage



Unijunction Oscillator

- The oscillating frequency is calculated as follows:

$$f_o \cong \frac{1}{R_T C_T \ln\left[1/\left(1-\eta\right)\right]}$$

- where, η = the unijunction transistor intrinsic stand-off ratio
- Typically, a unijunction transistor has a stand-off ratio from 0.4 to 0.6