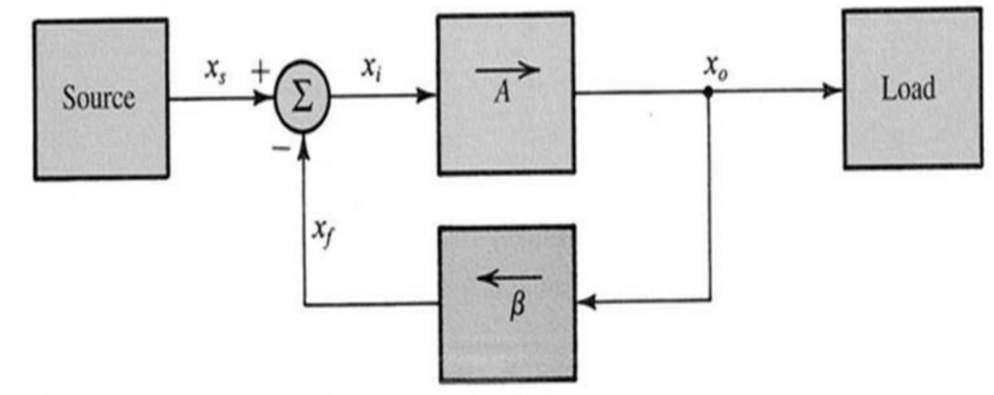
UNIT –I

Feedback Amplifiers : Feedback principle and concept, types of feedback, classification of amplifiers, feedback topologies, Characteristics of negative feedback amplifiers, Generalized analysis of feedback amplifiers, Performance comparison of feedback amplifiers, Method of analysis of feedback amplifiers.

FEEDBACK AMPLIFIER:



- Signal-flow diagram of a feedback amplifier
- Open-loop gain: A
- Feedback factor:
- Loop gain: A
- Amount of feedback: 1 + A

- Gain of the feedback amplifier (closed-loop gain):

Negative feedback:

- The feedback signal xf is subtracted from the source signal xs
- Negative feedback reduces the signal that appears at the input of the basic amplifier
- The gain of the feedback amplifier Af is smaller than open-loop gain A by a factor of

(1+A)

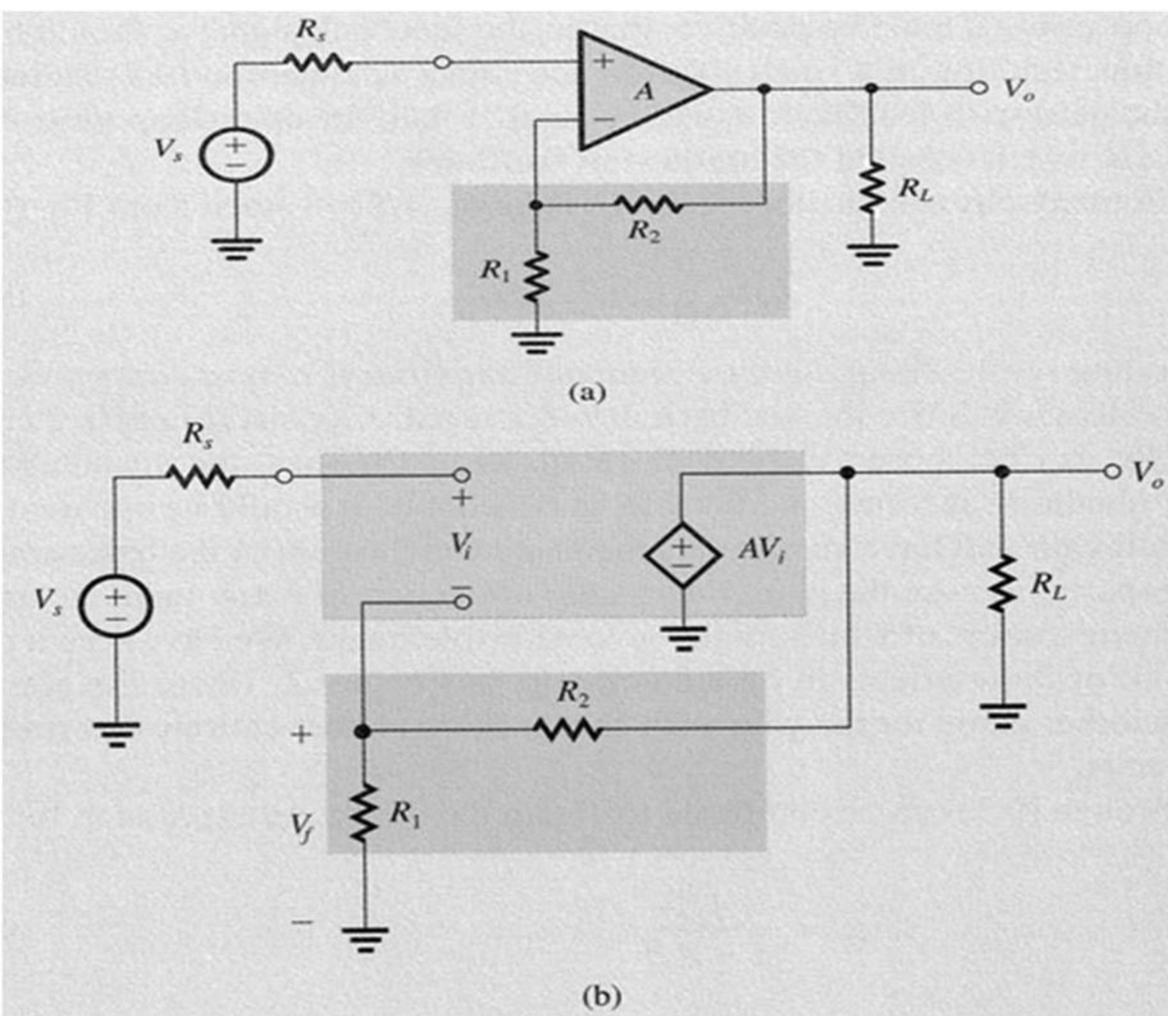
- The loop gain A is typically large (A >>1):
- The gain of the feedback amplifier (closed-loop gain)
- The closed-loop gain is almost entirely determined by the feedback network better

accuracy of Af.

- xf = xs(A)/(1+A) xs error signal xi = xs – xf

For Example, The feedback amplifier is based on an op amp with infinite input resistance and zero output resistance.

- Find an expression for the feedback factor.
- Find the condition under which the closed-loop gain Af is almost entirely determined by the feedback network.
- If the open-loop gain A = 10000 V/V, find R2/R1 to obtain a closed-loop gain Af of 10 V/V.
- What is the amount of feedback in decibel?
- If Vs = 1 V, find Vo, Vf and Vi.
- If A decreases by 20%, what is the corresponding decrease in Af ?



Some Properties of Negative Feedback

Gain de sensitivity:

- The negative reduces the change in the closed-loop gain due to open-loop gain variation

$$dA_f = \frac{dA}{(1+A\beta)^2} \rightarrow \frac{dA_f}{A_f} = \frac{1}{1+A\beta}\frac{dA}{A}$$

- Desensitivity factor: $1 + A$

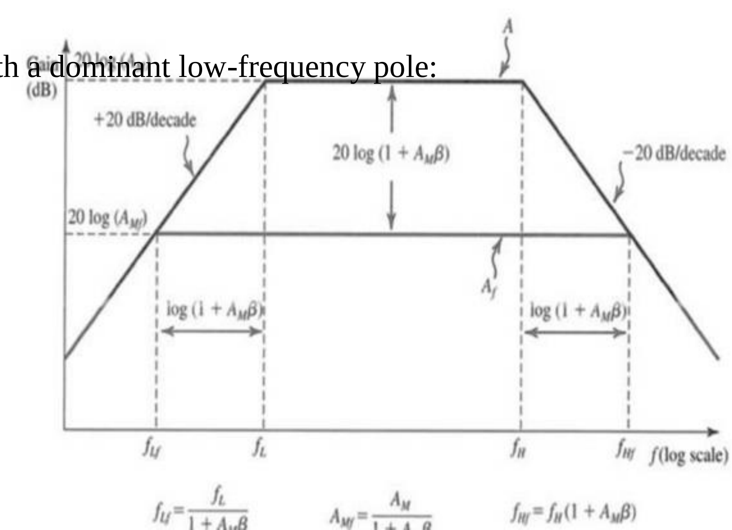
Bandwidth extension

High-frequency response of a single-pole amplifier:

$$A(s) = \frac{A_M}{1+s/\omega_H} \rightarrow A_f(s) = \frac{A_M/(1+A_M\beta)}{1+s/\omega_H(1+A_M\beta)}$$

Low-frequency response of an amplifier with a dominant low-frequency pole:

$$A(s) = \frac{sA_M}{s+\omega_L} \rightarrow A_f(s) = \frac{sA_M/(1+A_M\beta)}{s+\omega_L/(1+A_M\beta)}$$



Negative feedback:

Reduces the gain by a factor of (1+AM)

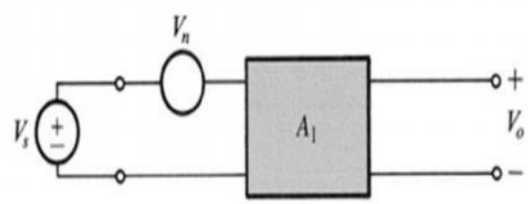
Extends the bandwidth by a factor of (1+AM)

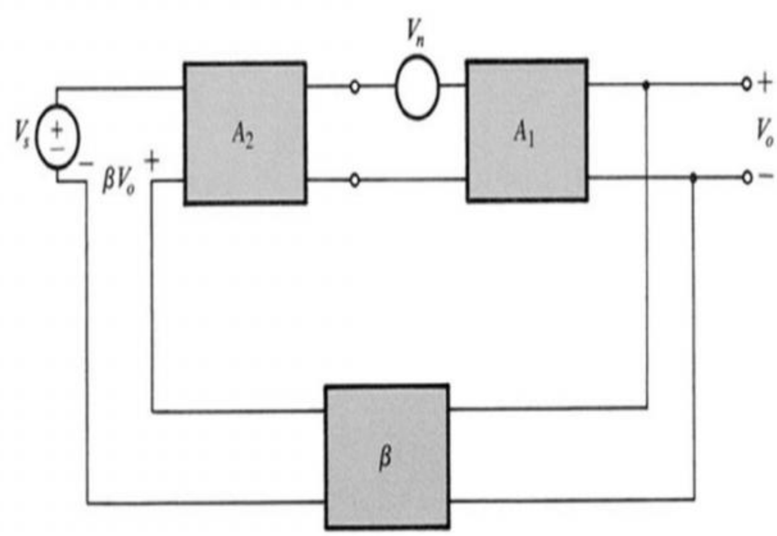
Interference reduction

- The signal-to-noise ratio:
  - The amplifier suffers from interference introduced at the input of the amplifier
  - Signal-to-noise ratio: S/I = Vs/Vn

- Enhancement of the signal-to-noise ratio:
  - Precede the original amplifier A1 by a clean amplifier A2
  - Use negative feedback to keep the overall gain constant.

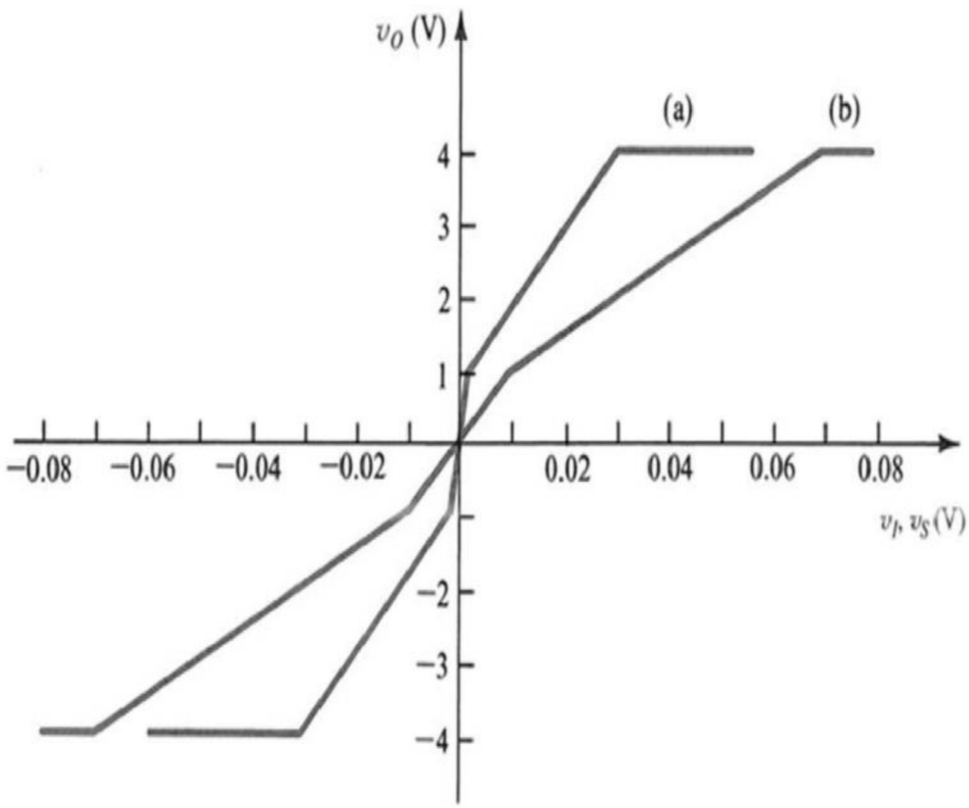
$$V_0 = V_s \frac{A_1 A_2}{1 + A_1 A_2 \beta} + V_n \frac{A_1}{1 + A_1 A_2 \beta} \rightarrow \frac{S}{I} = \frac{V_s}{V_n} A_2$$





Reduction in nonlinear distortion:

The amplifier transfer characteristic is linearised through the application of negative feedback.



□ = 0.01

| | | |

A changes from 1000 to 100

$$A_{f1} = \frac{1000}{1+1000\times 0.01} = 90.9$$

$$A_{f2} = \frac{100}{1+100\times 0.01} = 50$$

The Four Basic Feedback Topologies:

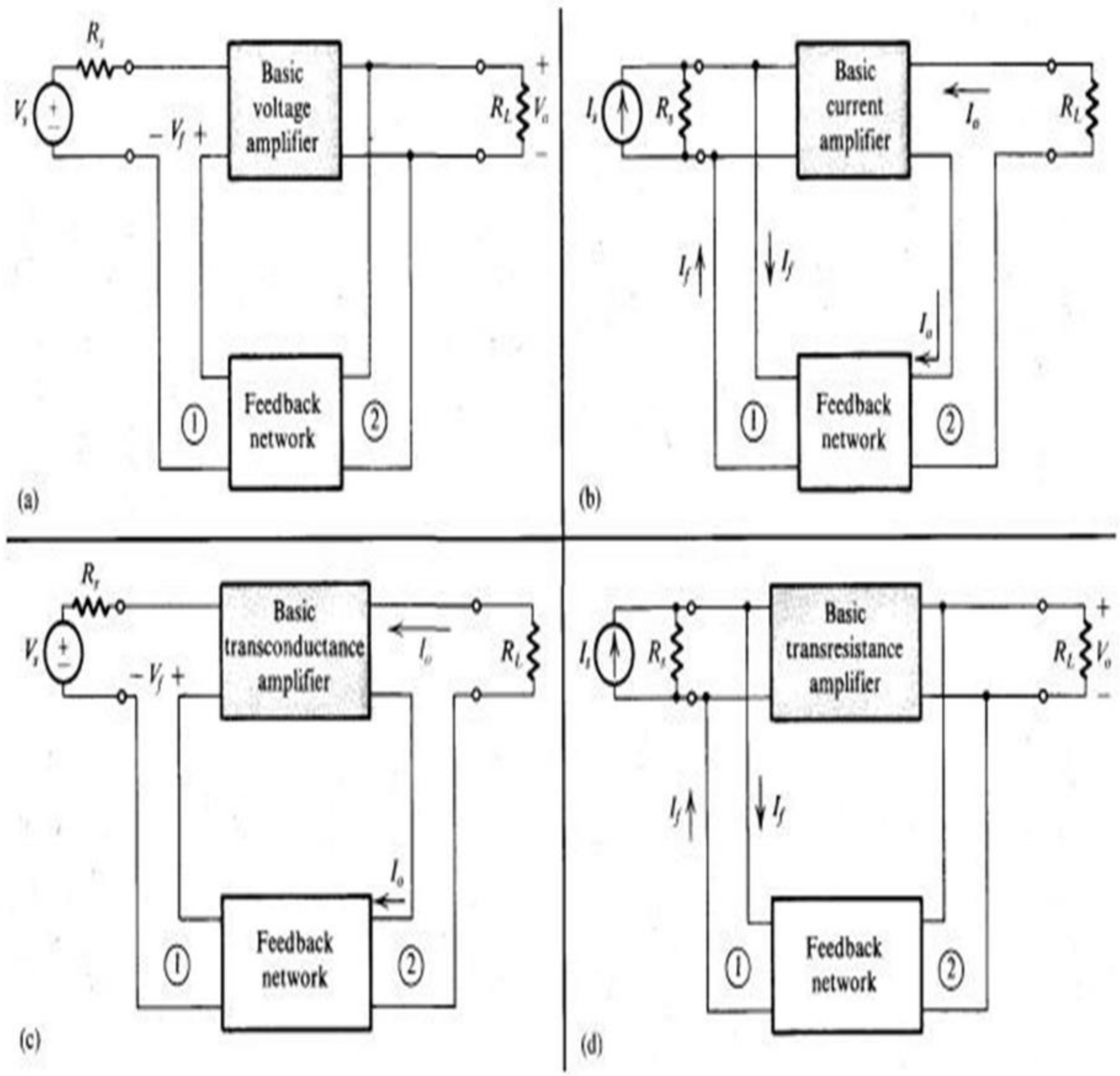


Fig. The four basic feedback topologies: (a) voltage-sampling series-mixing (series-shunt) topology; (b) current-sampling shunt-mixing (shunt-series) topology; (c) current-sampling series-mixing (series-series) topology; (d) voltage-sampling shunt-mixing (shunt-shunt) topology.

Method of analysis of Feedback Amplifiers:

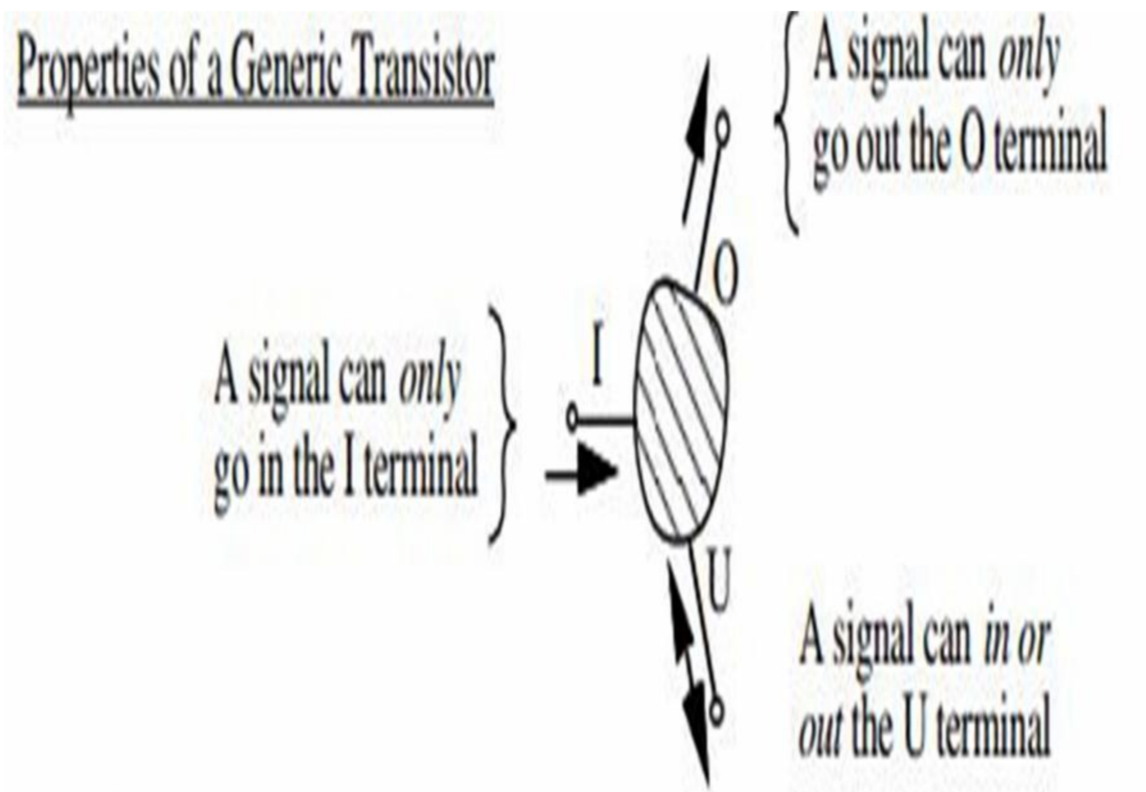
1. Identify the topology.

2. Determine whether the feedback is positive or negative.

3. Open the loop and calculate A, ß, Ri, and Ro.

4. Use the Table to find Af, Rif and Rof or AF, RiF, and RoF.

5. Use the information in 4 to find whatever is required (v_{out}/v_{in}, R_{in}, R_{out}, etc.)



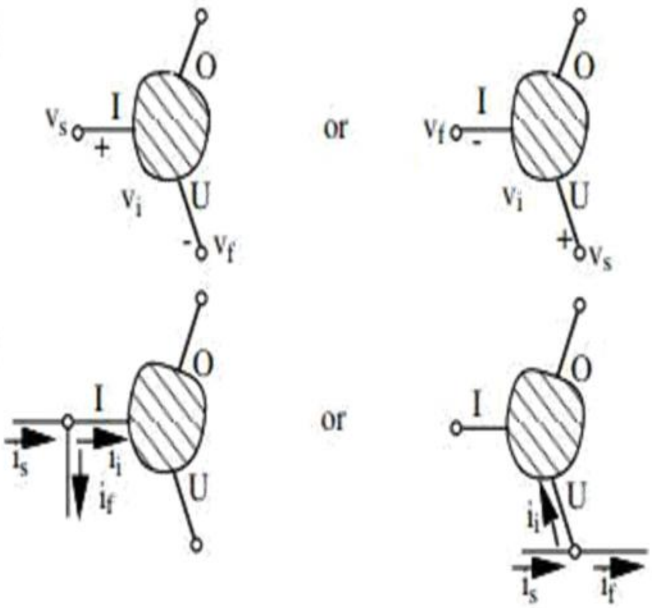
Identification of the Feedback Topology

Isolate the input and output transistor(s) and apply the following identification.

<u>Input</u>

Series:

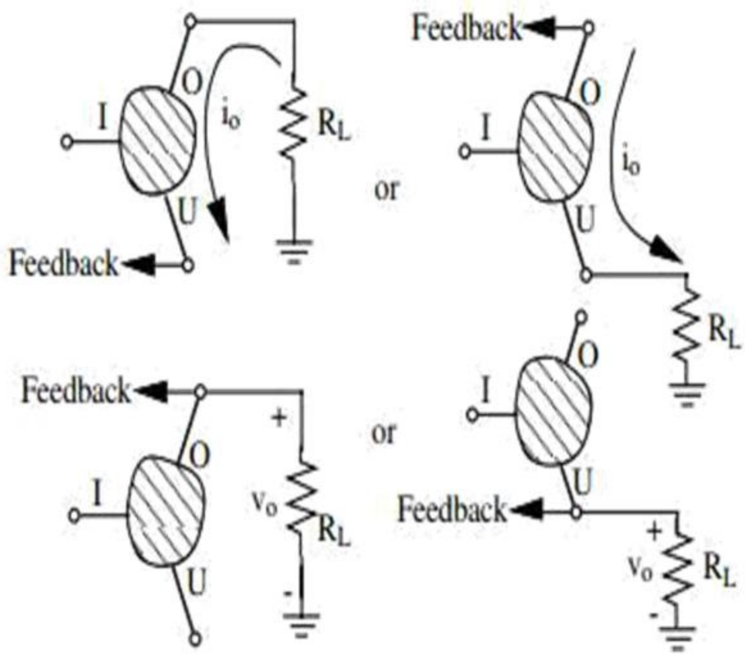
Shunt:



<u>Output</u>

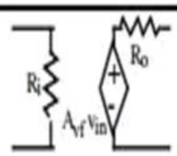
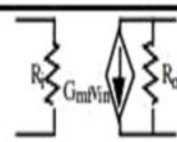
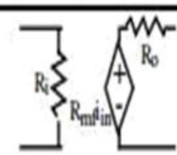
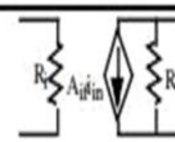
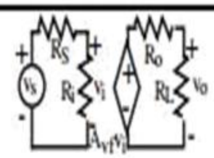
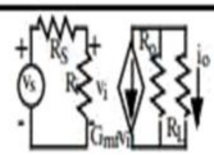
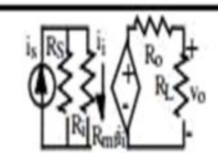
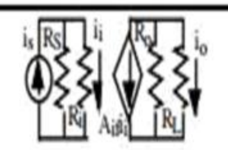
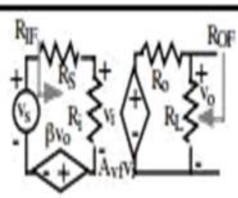
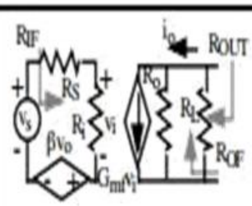
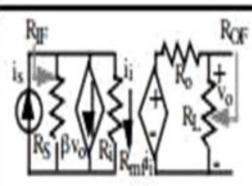
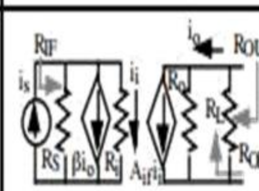
Series:

Shunt:



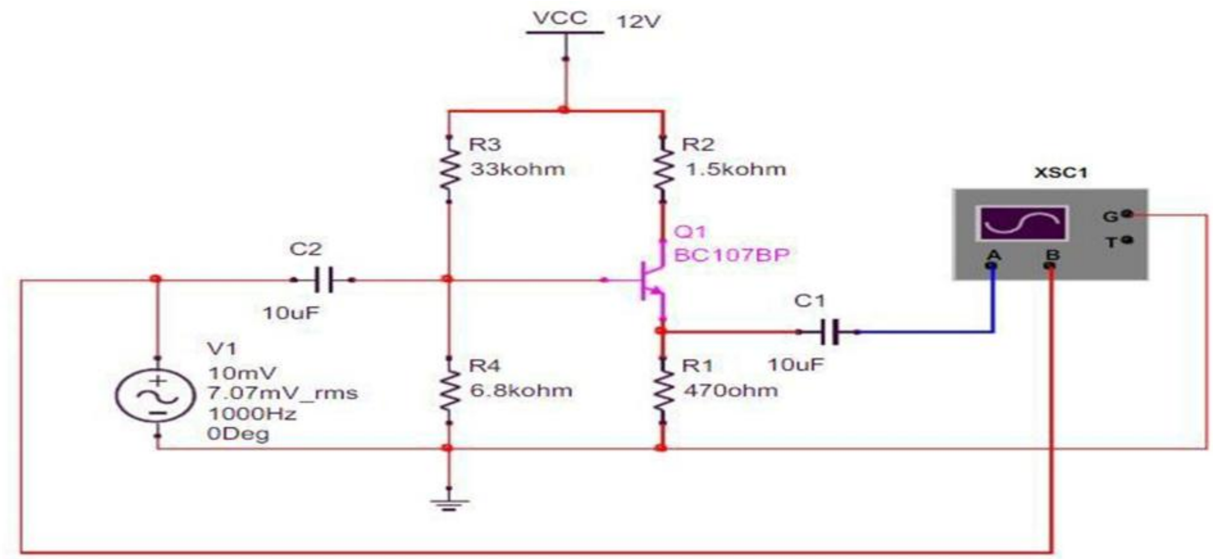
Performance comparison of feedback amplifiers:

Summary of the Important Relationships of Open-loop and Closed-loop Feedback Amplifiers.

Quantity	Voltage Amplifier	Transconductance Amplifier	Transresistance Amplifier	Current Amplifier
Input-output variable	Voltage-voltage	Voltage-current	Current-voltage	Current-current
Small Signal Model				
Small Signal Amplifier with Source & Load				
Ideal R_S	$R_S = 0$ or $R_S << R_i$	$R_S = 0$ or $R_S << R_i$	$R_S = \infty$ or $R_S >> R_i$	$R_S = \infty$ or $R_S >> R_i$
Ideal R_L	$R_L = \infty$ or $R_L >> R_o$	$R_L = 0$ or $R_L << R_o$	$R_L = \infty$ or $R_L >> R_o$	$R_L = 0$ or $R_L << R_o$
Overall Forward Gain	$A_V = \frac{R_i R_L A_{vf}}{(R_S+R_i)(R_L+R_o)}$	$G_M = \frac{R_i R_o G_{mf}}{(R_S+Ri)(R_L+R_o)}$	$R_M = \frac{R_S R_L R_{mf}}{(R_S+Ri)(R_L+R_o)}$	$A_I = \frac{R_S R_o A_{if}}{(R_S+Ri)(R_L+R_o)}$
Feedback Topology	Series-shunt	Series-series	Shunt-shunt	Shunt-series
Ideal ß, finite R_S and R_L Feedback Small Signal Models				
Closed-Loop Gain (Ideal R_S and R_L)	$A_{vF} = \frac{A_{vf}}{(1+A_{vf}ß_v)}$	$G_{mF} = \frac{G_{mf}}{(1+G_{mf}ß_g)}$	$R_{mF} = \frac{R_{mf}}{(1+R_{mf}ß_r)}$	$A_{iF} = \frac{A_{if}}{(1+A_{if}ß_i)}$

Closed-Loop Input Resistance (Ideal R_S and R_L)	$R_{iF} = R_i(1 + A_{vf}\beta_v)$	$R_{iF} = R_i(1 + G_{mf}\beta_g)$	$R_{iF} = \frac{R_i}{1 + R_{mf}\beta_r}$	$R_{iF} = \frac{R_i}{1 + A_{if}\beta_i}$
Closed-Loop Output Resistance (Ideal R_S and R_L)	$R_{oF} = \frac{R_o}{1 + A_{vf}\beta_v}$	$R_{oF} = R_o(1 + R_{mf}\beta_g)$	$R_{oF} = \frac{R_o}{1 + R_{mf}\beta_r}$	$R_{oF} = R_o(1 + A_{if}\beta_i)$
Closed-Loop Gain	$A_{VF} = \frac{A_V}{(1+A_V\beta_v)}$	$G_{MF} = \frac{G_M}{(1+G_M\beta_g)}$	$R_{MF} = \frac{R_M}{(1+R_M\beta_r)}$	$A_{IF} = \frac{A_I}{(1+A_I\beta_i)}$
Closed-Loop Input Resistance	$R_{IF} =$ $(R_i+R_S)(1+A_V\beta_v)$	$R_{IF} =$ $(R_i+R_S)(1 + G_M\beta_g)$	$R_{IF} = \frac{\frac{R_iR_S}{R_i+R_S}}{1 + R_M\beta_r}$	$R_{IF} = \frac{\frac{R_iR_S}{R_i+R_S}}{1 + A_I\beta_i}$
Closed-Loop Output Resistance	$R_{OF} = \frac{\frac{R_oR_L}{R_o+R_L}}{1 + A_V\beta_V}$	$R_{OF} =$ $(R_o+R_L)(1+G_M\beta_g)$	$R_{OF} = \frac{\frac{R_oR_L}{R_o+R_L}}{1 + R_M\beta_r}$	$R_{OF} =$ $(R_o+R_L)(1+A_I\beta_i)$
Output Resistance of Series Output Fb. Ckt	$R_{OUT} = R_{OF}$	$R_{OUT} = \frac{R_L}{R_{OF}}(R_{OF}-R_L)$	$R_{OUT} = R_{OF}$	$R_{OUT} = \frac{R_L}{R_{OF}}(R_{OF}-R_L)$

In voltage series feedback amplifier, sampling is voltage and series mixing indicates voltage mixing. As both input and output are voltage signals and is said to be voltage amplifier with gain A_{vf}.



Band width is defined as the range frequencies over which gain is greater than or equal to 0.707 times the maximum gain or up to 3 dB down from the maximum gain

$$\text{Bandwidth (BW)} = f_h - f_l$$

Where f_h= Upper cutoff frequency

And f_l= Lower cutoff frequency.

Cutoff frequency is the frequency at which the gain is 0.707 times the maximum gain or 3dB down from the maximum gain. In all feedback amplifiers we use negative feedback, so gain is reduced and bandwidth is increased

$$\mathbf{A_{vf} = Av/[1+A_v\beta]}$$

$$\mathbf{And\ BW_f. = BW\ [1+ A_v\beta]}$$

Where A_{vf} = Gain with feedback

Av= Gain without feedback

β=feedback gain

BW_f = Bandwidth with feedback and

BW = Bandwidth without feedback Output resistance will decrease due to shunt connection at output and input resistance will increase due to series connection at input.

So $\mathbf{R_{0f} = R_0/[1+Av\beta]}$ **and**

$\mathbf{R_{if} = R_i[1+Av\beta]}$.

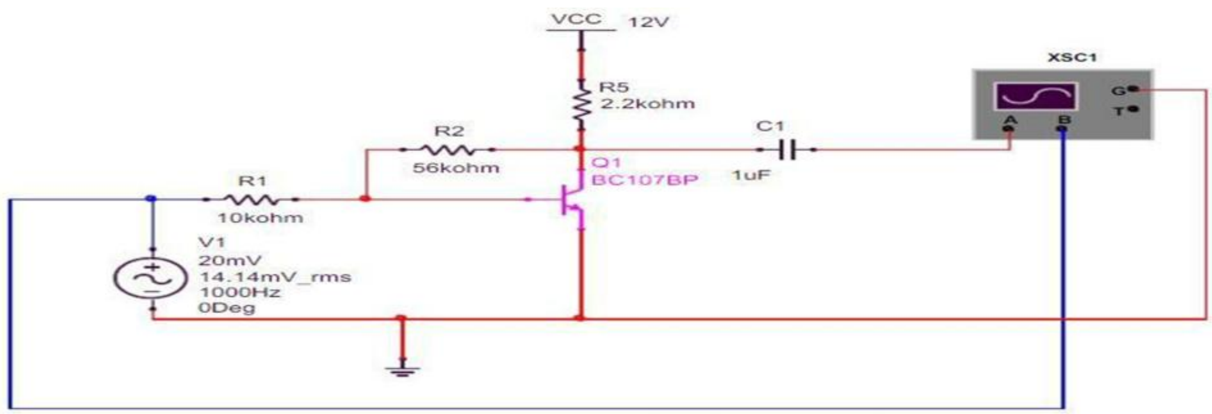
Where R 0f = Output resistance with feedback

R_0= Output resistance without feedback.

R_{if}= Input resistance with feedback

R_i= Input resistance without feedback

In voltage shunt feedback amplifier, sampling is voltage and shunt mixing indicates current mixing. As input is current signal and output is voltage signal, so it is said to be trans-resistance amplifier with gain R_{mf}.



Band width is defined as the range frequencies over which gain is greater than or equal to 0.707 times the maximum gain or up to 3 dB down from the maximum gain.

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Cutoff frequency is the frequency at which the gain is 0.707 times the maximum gain or 3dB down from the maximum gain. In all feedback amplifiers we use negative feedback, so gain is reduced and bandwidth is increased.

$$\mathbf{R_{mf} = Rm/[1+R_m\beta]}$$

$$\mathbf{And\ BW_f = BW\ [1+ R_m\beta]}$$

Where

R_{mf} = Gain with feedback

R_m= Gain without feedback

β=feedback gain

BW = Bandwidth without feedback

Output resistance and input resistance both will decrease due to shunt connections at input and output. So

$$\mathbf{R_{0f} = R_0/[1+ R_m\ \beta]\ and}$$

$$\mathbf{R_{if} = R_i/[1+ R_m\ \beta].}$$

Where R 0f = Output resistance with feedback

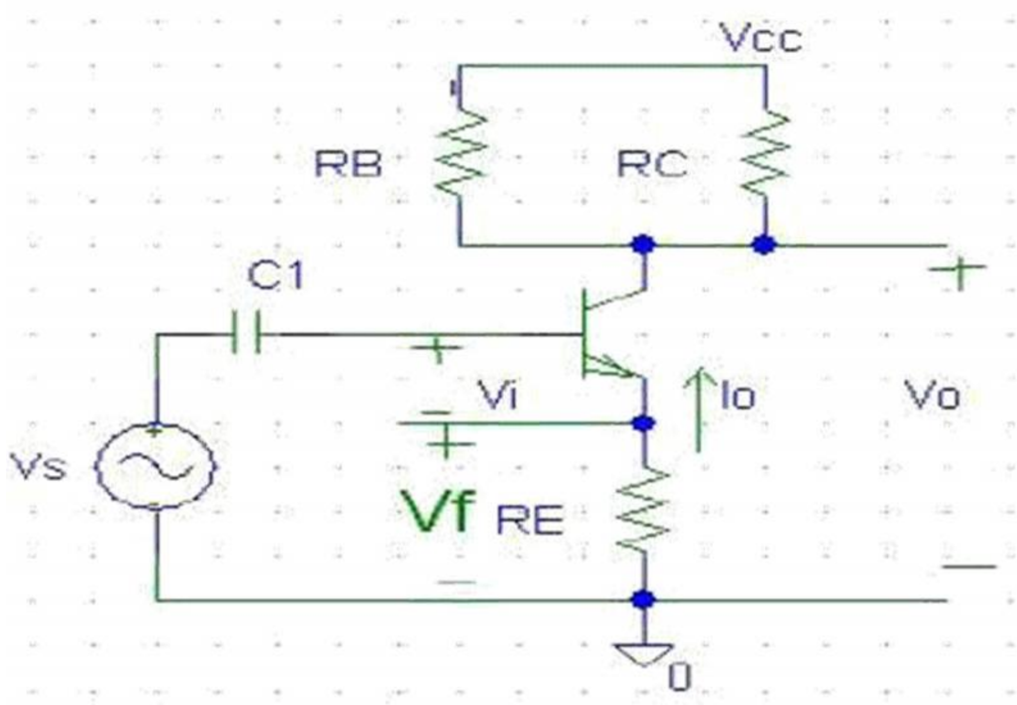
R_0= Output resistance without feedback.

R_{if}= Input resistance with feedback

R_i= Input resistance without feedback

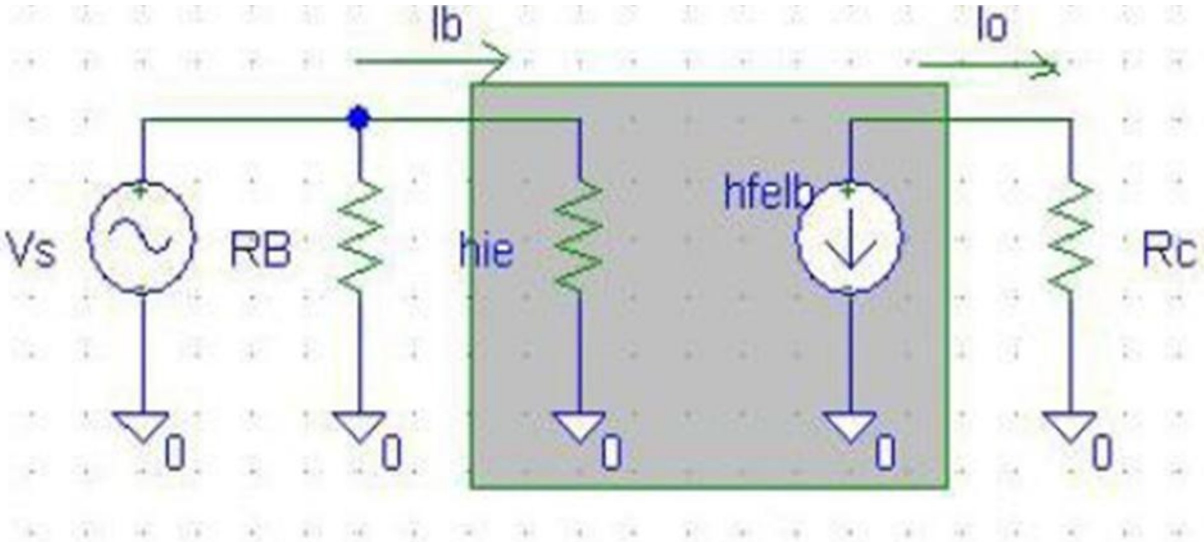
Current series feedback

- Feedback technique is to sample the output current (Io) and return a proportional voltage in series.
- It stabilizes the amplifier gain, the current series feedback connection increases the input resistance.
- In this circuit, emitter of this stage has an un bypassed emitter, it effectively has current-series feedback.
- The current through RE results in feedback voltage that opposes the source signal applied so that the output voltage Vo is reduced.



• To remove the current-series feedback, the emitter resistor must be either removed or bypassed by a capacitor (as is done in most of the amplifiers)

The fig below shows the equivalent circuit for current series feedback


Ib
Io
Vs
RB
hie
hfeIb
Rc
0
0
0
0
0

Gain, input and output impedance for this condition is,

$$A_f = \frac{I_o}{V_s} = \frac{A}{1 + A\beta} = \frac{-h_{fe} / h_{ie}}{1 + (-R_E)\left(\frac{-h_{fe}}{h_{ie} + R_E}\right)}$$

$$Z_{if} = Z_i(1 + A\beta) \cong h_{ie}\left(1 + \frac{h_{fe}R_E}{h_{ie}}\right)$$

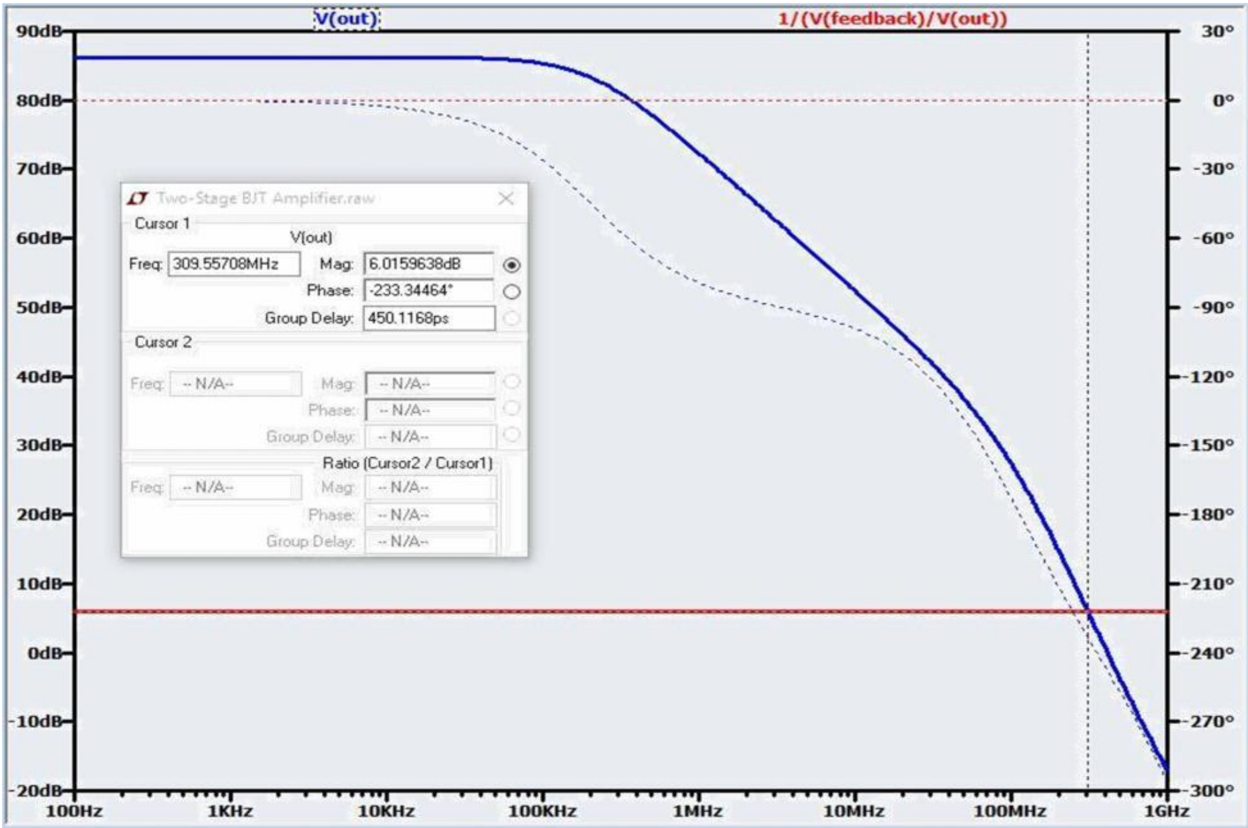
$$Z_{of} = Z_o(1 + A\beta) \cong R_c\left(1 + \frac{h_{fe}R_E}{h_{ie}}\right)$$

$with - feedback..A;$

$$A_{vf} = \frac{V_o}{V_s} = \frac{I_o R_c}{V_s} = \left(\frac{I_o}{V_s}\right)R_c = A_f R_C \cong \frac{-h_{fe}R_C}{h_{ie} + h_{fe}R_E}$$

We now know that by plotting the gain and phase shift of a negative feedback amplifier's loop gain—denoted by *Aβ*, where *A* is always a function of frequency and *β* can be considered a function of frequency if necessary—we can determine two things: 1) whether the amplifier is stable, and 2) whether the amplifier is *sufficiently* stable (rather than *marginally* stable). The first determination is based on the stability criterion, which states that the magnitude of the loop gain must be less than unity at the frequency where the phase shift of the loop gain is 180°. The second is based on the amount of gain margin or phase margin; a rule of thumb is that the phase margin should be at least 45°.

It turns out that we can effectively analyze stability using an alternative and somewhat simplified approach in which open-loop gain *A* and feedback factor *β* are depicted as separate curves on the same axes. Consider the following plot for the discrete BJT amplifier with a frequency-independent (i.e., resistor-only) feedback network configured for $\beta = 0.5$:



V(out)
1/(V(feedback)/V(out))
90dB
80dB
70dB
60dB
50dB
40dB
30dB
20dB
10dB
0dB
-10dB
-20dB
30°
0°
-30°
-60°
-90°
-120°
-150°
-180°
-210°
-240°
-270°
-300°
100Hz
1KHz
10KHz
100KHz
1MHz
10MHz
100MHz
1GHz
Two-Stage BJT Amplifier.raw
Cursor 1
V(out)
Freq: 309.55708MHz
Mag: 6.0159638dB
Phase: -233.34464°
Group Delay: 450.1168ps
Cursor 2
Freq: -- N/A--
Mag: -- N/A--
Phase: -- N/A--
Group Delay: -- N/A--
Ratio (Cursor2 / Cursor1)
Freq: -- N/A--
Mag: -- N/A--
Phase: -- N/A--
Group Delay: -- N/A--

Here you see V(out), which corresponds to the open-loop gain, and 1/(V(feedback)/V(out)). If you recall that β is the percentage (expressed as a decimal) of the output fed back and subtracted from the input, you will surely recognize that this second trace is simply $1/\beta$. So why did we plot $1/\beta$? Well, we know that loop gain is A multiplied by β, but in this plot the y-axis is in decibels and is thus logarithmic. Our high school math teachers taught us that multiplication of ordinary numbers corresponds to addition with logarithmic values, and likewise numerical division corresponds to logarithmic subtraction. Thus, a logarithmic plot of A multiplied by β can be represented as the logarithmic plot of A **plus** the logarithmic plot of β. Remember, though, that the above plot includes not β but rather $1/\beta$, which is the equivalent of **negative** β on a logarithmic scale. Let's use some numbers to clarify this:

$$\beta=0.5 \Rightarrow 20\log(\beta)\approx -6\text{ dB}\beta=0.5 \Rightarrow 20\log\ (\beta)\approx -6\text{ dB}$$

$$1\beta=2 \Rightarrow 20\log(1\beta)\approx 6\text{ dB}1\beta=2 \Rightarrow 20\log\ (1\beta)\approx 6\text{ dB}$$

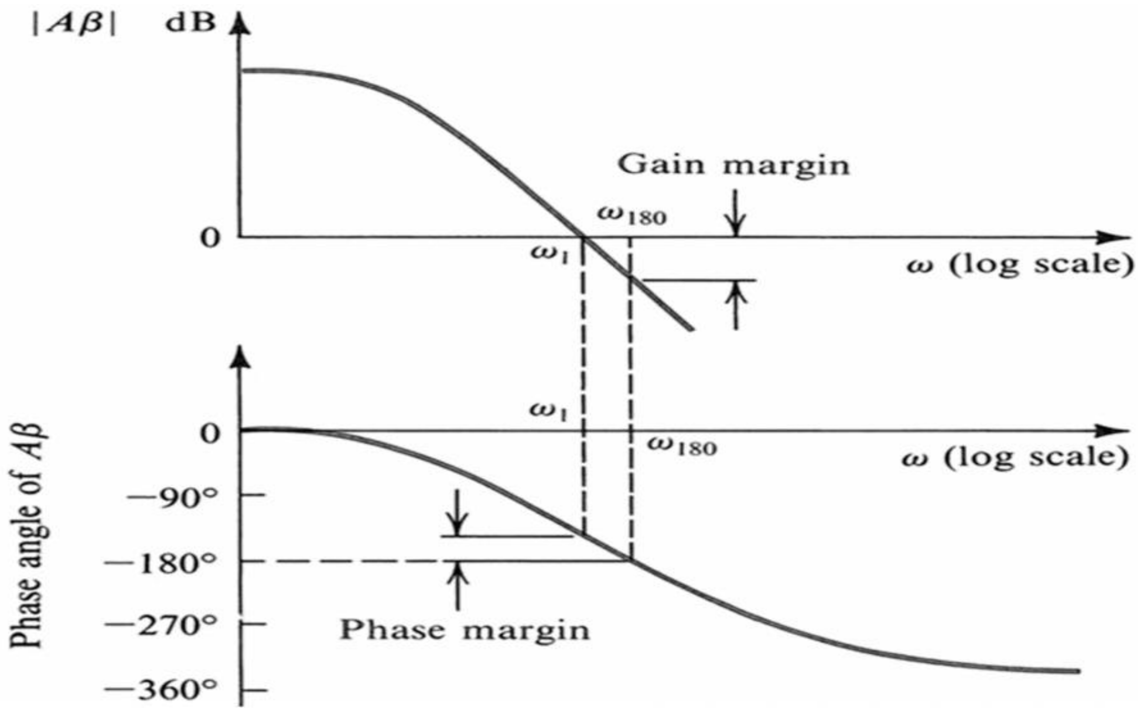
Thus, in this logarithmic plot, we have 20log(A) and -20log(β), which means that to reconstruct 20log($A\beta$) we need to **subtract the 1/β curve from the A curve**:

20log(Aβ)=20log(A)+20log(β) ⇒ 20log(Aβ)=20log(A)−(−20log(β))20log (Aβ)=20log (A)+20 log (β) ⇒ 20log (Aβ)=20log (A)−(−20log (β))

⇒ 20log(Aβ)=20log(A)−20log(1β).

Gain and phase margin

- The stability of a feedback amplifier is determined by examining its loop gain as a function of frequency.
- One of the simplest means is through the use of Bode plot for A .
- Stability is ensured if the magnitude of the loop gain is less than unity at a frequency shift of 180 .
- Gain margin:
  - The difference between the value | A | of at 180 and unity.
  - Gain margin represents the amount by which the loop gain can be increased while maintaining stability.
- Phase margin:
  - A feedback amplifier is stable if the phase is less than 180 at a frequency for which |Aβ | =1.
  - A feedback amplifier is unstable if the phase is in excess of 180 at a frequency for which | A | =1.
  - The difference between the a frequency for which | A | =1 and 180 .



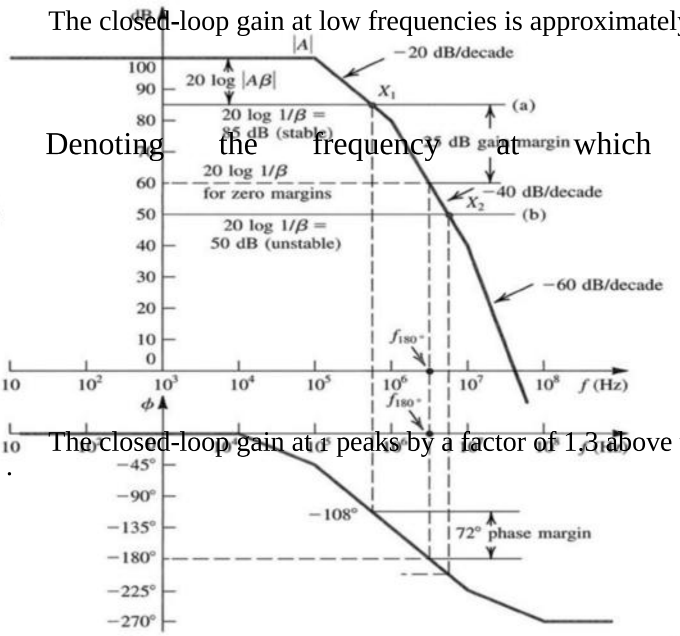
Effect of phase margin on closed-loop response:

- Consider a feedback amplifier with a large low-frequency loop gain (A_0 >> 1).

- The closed-loop gain at low frequencies is approximately 1/ .

- Denoting the frequency at which | A | =1 by μ1:

A



$$A = \frac{10^5}{(1 + jf/10^5)(1 + jf/10^6)(1 + jf/10^7)}$$

$$\phi = -\left[\tan^{-1}(f/10^5) + \tan^{-1}(f/10^6) + \tan^{-1}(f/10^7)\right]$$

- The closed-loop gain at 1 peaks by a factor of 1.3 above the low-frequency gain for a phase margin of 45 .

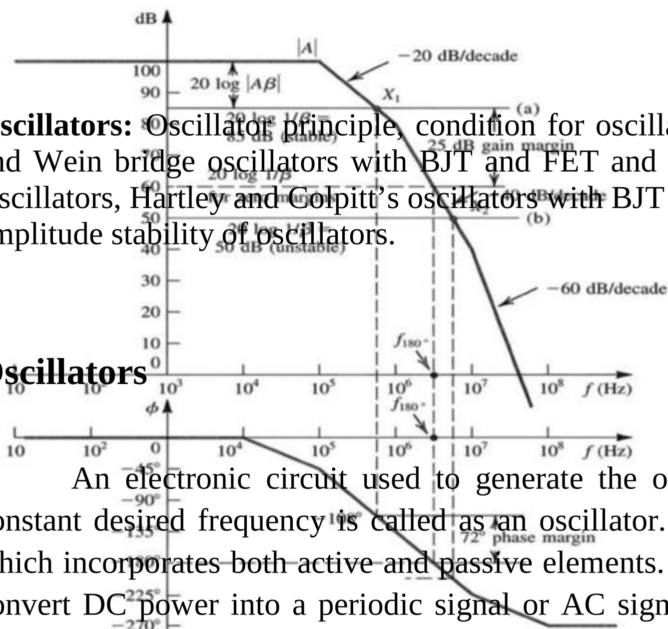
$$A_f(j\omega_1) = \frac{A(j\omega_1)}{1 + A(j\omega_1)\beta} = \frac{1}{\beta}\frac{e^{-j\theta}}{1+e^{-j\theta}}$$

$$|A_f(j\omega_1)| = \frac{1/\beta}{|1+e^{-j\theta}|}$$

- This peaking increase as the phase margin is reduced, eventually reaching infinite when the phase margin is zero (sustained oscillations).

An alternative approach for investigating stability

- In a Bode plot, the difference between 20 log|*A*(j μ)| and 20 log(1/) is 20 log| *A* |.



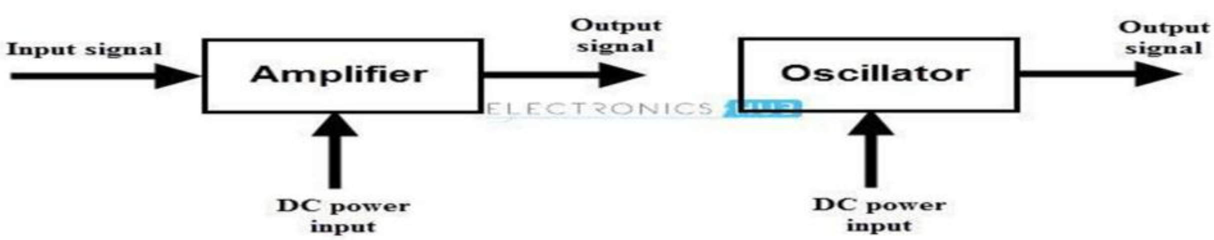
$$A = \frac{10^5}{(1 + jf/10^5)(1 + jf/10^6)(1 + jf/10^7)}$$

$$\phi = -\left[\tan^{-1}(f/10^5) + \tan^{-1}(f/10^6) + \tan^{-1}(f/10^7)\right]$$

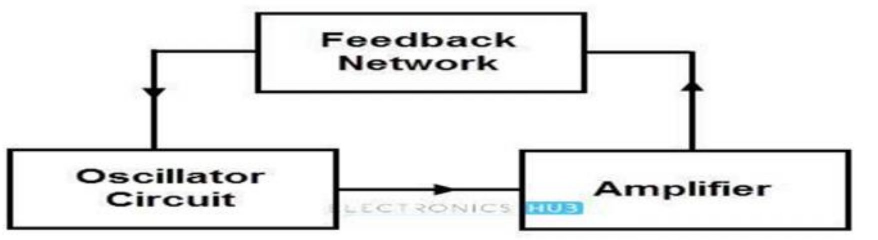
Oscillators: Oscillator principle, condition for oscillations, types of oscillators, RC-phase shift and Wein bridge oscillators with BJT and FET and their analysis, Generalized analysis of LC Oscillators, Hartley and Colpitt's oscillators with BJT and FET and their analysis, Frequency and amplitude stability of oscillators.

Oscillators

An electronic circuit used to generate the output signal with constant amplitude and constant desired frequency is called as an oscillator. It is also called as a waveform generator which incorporates both active and passive elements. The primary function of an oscillator is to convert DC power into a periodic signal or AC signal at a very high frequency. An oscillator does not require any external input signal to produce sinusoidal or other repetitive waveforms of desired magnitude and frequency at the output and even without use of any mechanical moving parts.



In case of amplifiers, the energy conversion starts as long as the input signal is present at the input, i.e., amplifier produces an output signal whose frequency or waveform is similar to the input signal but magnitude or power level is generally high. The output signal will be absent if there is no input signal at the input.In contrast, to start or maintain the conversion process an oscillator does not require any input signal as shown figure. As long as the DC power is connected to the oscillator circuit, it keeps on producing an output signal with frequency decided by components in it.

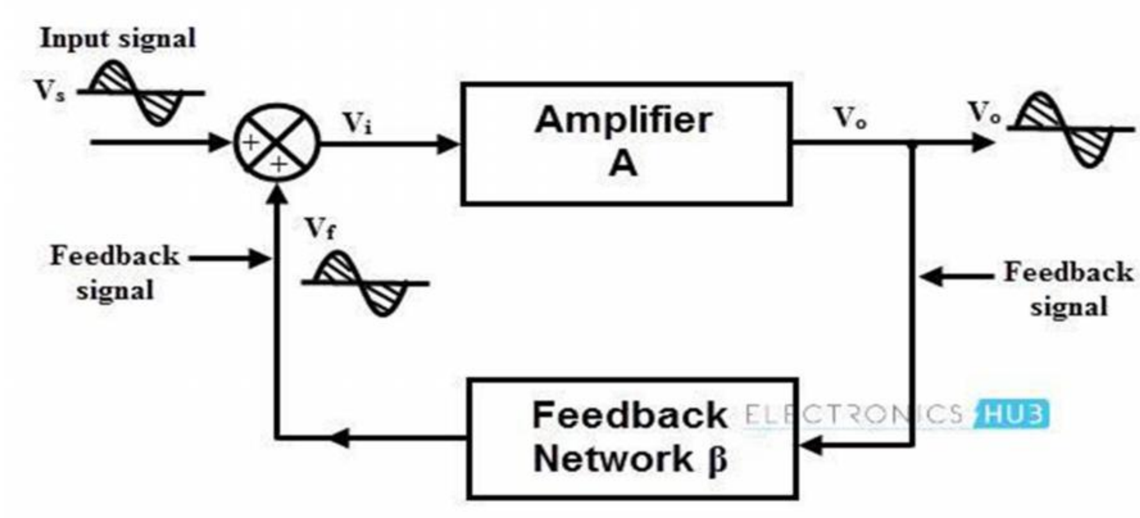


The above figure shows the block diagram of an oscillator. An oscillator circuit uses a vacuum tube or a transistor to generate an AC output. The output oscillations are produced by the tank circuit components either as R and C or L and C. For continuously generating output without the requirement of any input from preceding stage, a feedback circuit is used.

From the above block diagram, oscillator circuit produces oscillations that are further amplified by the amplifier. A feedback network gets a portion of the amplifier output and feeds it the oscillator circuit in correct phase and magnitude. Therefore, un damped electrical oscillations are produced , by continuously supplying losses that occur in the tank circuit.

Oscillators Theory

The main statement of the oscillator is that the oscillation is achieved through positive feedback which generates the output signal without input signal. Also, the voltage gain of the amplifier increases with the increase in the amount of positive feedback. In order to understand this concept, let us consider a non-inverting amplifier with a voltage gain ‘A’ and a positive feedback network with feedback gain of β as shown in figure.



Let us assume that a sinusoidal input signal Vs is applied at the input. Since the amplifier is non-inverting, the output signal Vo is in phase with Vs. A feedback network feeds the part of Vo to the input and the amount Vo fed back depends on the feedback network gain β. No phase shift is introduced by this feedback network and hence the feedback voltage or signal Vf is in phase with Vs. A feedback is said to be positive when the phase of the feedback signal is same as that of the input signal. The open loop gain 'A' of the amplifier is the ratio of output voltage to the input voltage, i.e.,

$$A = Vo/Vi$$

By considering the effect of feedback, the ratio of net output voltage Vo and input supply Vs called as a closed loop gain Af (gain with feedback).

$$Af = Vo/Vs$$

Since the feedback is positive, the input to the amplifier is generated by adding Vf to the Vs, $Vi = Vs + Vf$

Depends on the feedback gain β, the value of the feedback voltage is varied, i.e.,

$$Vf = \beta\ Vo$$

Substituting in the above equation,

$$Vi = Vs + \beta\ Vo$$

$$Vs = Vi - \beta\ Vo$$

Then the gain becomes

$$Af = Vo/\ (Vi - \beta\ Vo)$$

By dividing both numerator and denominator by Vi, we get

$$Af = (Vo\ /\ Vi)/\ (1 - \beta)\ (Vo\ /\ Vi)$$

$$Af = A/\ (1 - A\ \beta) \text{ since } A = Vo/Vi$$

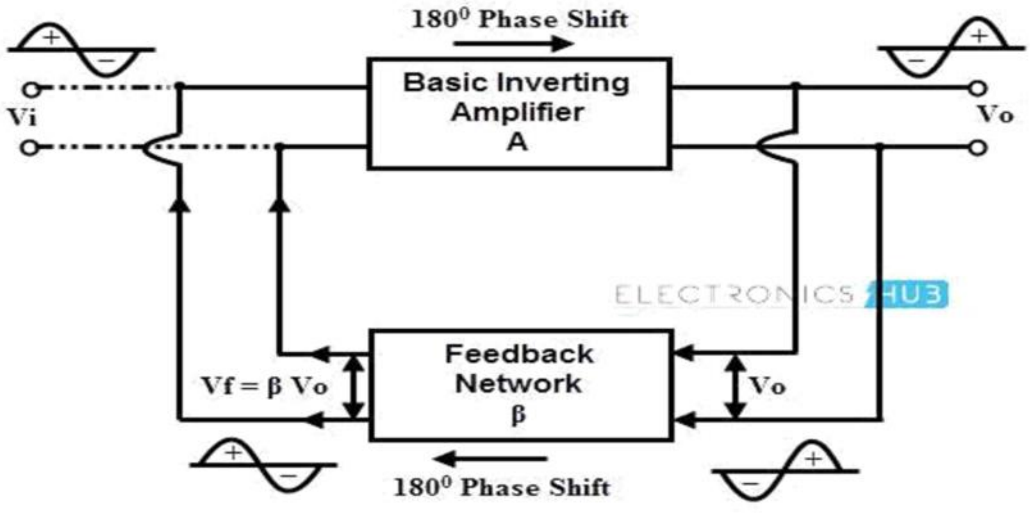
Where Aβ is the loop gain and if Aβ = 1, then Af becomes infinity. From the above expression, it is clear that even without external input (Vs = 0), the circuit can generate the output just by feeding a part of the output as its own input. And also closed loop gain increases with increase in amount of positive feedback gain. The oscillation rate or frequency depends on amplifier or feedback network or both.

Barkhausen Criterion or Conditions for Oscillation

The circuit will oscillate when two conditions, called as Barkhausen's criteria are met. These two conditions are

1. **The loop gain must be unity or greater**
2. **The feedback signal feeding back at the input must be phase shifted by 360 degrees** (which is same as zero degrees). In most of the circuits, an inverting amplifier is used to produce 180 degrees phase shift and additional 180 degrees phase shift is provided by the feedback network. At only one particular frequency, a tuned inductor-capacitor (LC circuit) circuit provides this 180 degrees phase shift.

Let us know how these conditions can be achieved.



Consider the same circuit which we have taken in oscillator theory. The amplifier is a basic inverting amplifier and it produces a phase shift of 180 degrees between input and output.

The input to be applied to the amplifier is derived from the output Vo by the feedback network. Since the output is out of phase with Vi. So the feedback network must ensure a phase shift of 180 degrees while feeding the output to the input. This is nothing but ensuring positive feedback.

Let us consider that a fictitious voltage, Vi is applied at the input of amplifier,

then Vo = A Vi

The amount of feedback voltage is decided by the feedback network gain,

$$V_f = -\beta V_o$$

This negative sign indicates 180 degrees phase shift.

Substituting Vo in above equation, we get

$$V_f = -A\beta V_i$$

In oscillator, the feedback output must drive the amplifier, hence Vf must act as Vi. For achieving this term $-A\beta$ in the above expression should be 1, i.e.,

$$V_f = V_s \text{ when } -A\beta = 1.$$

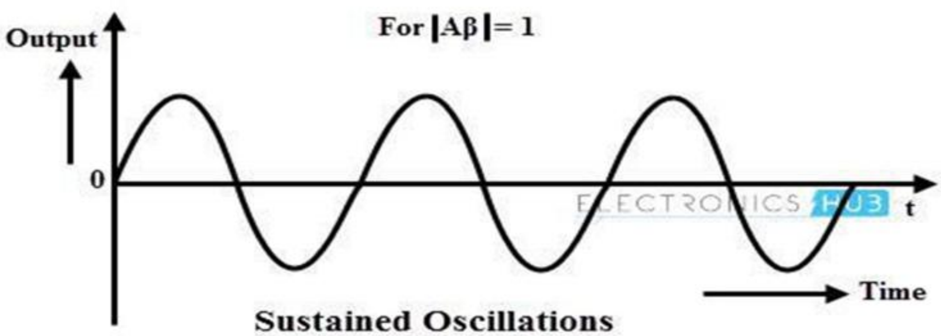
This condition is called as Barkhausen criterion for oscillation.

Therefore, $A\beta = -1 + j0$. This means that the magnitude of $A\beta$ (modulus of $A\beta$) is equal to 1. In addition to the magnitude, the phase of the Vs must be same as Vi. In order to perform this, feedback network should introduce a phase shift of 180 degrees in addition to phase shift (180 degrees) introduced by the amplifier.

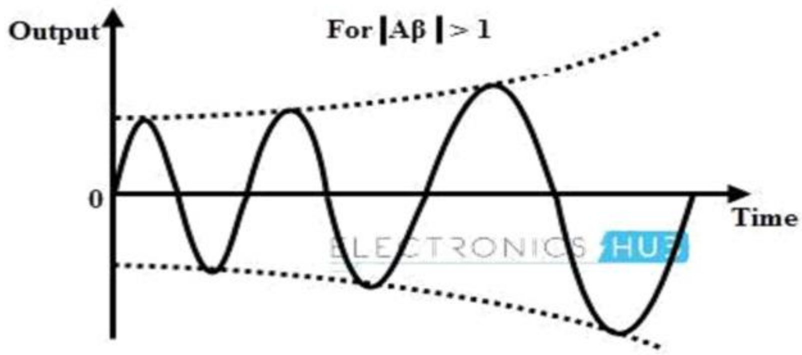
So the total phase shift around the loop is 360 degrees. Thus, under these conditions the oscillator can oscillate or produce the waveform without applying any input (that's why we have considered as fictitious voltage). It is important to know that how the oscillator starts to oscillate even without input signal in practice? The oscillator starts generating oscillations by amplifying the noise voltage which is always present. This noise voltage is result of the movement of free electrons under the influence of room temperature. This noise voltage is not exactly in sinusoidal due to saturation conditions of practical circuit. However, this nose signal will be sinusoidal when A β value is close to one. In practice modulus of A β is made greater than 1 initially, to amplify the small noise voltage. Later the circuit itself adjust to get modulus of A β is equal to one and with a phase shift of 360 degrees.

Nature of Oscillations

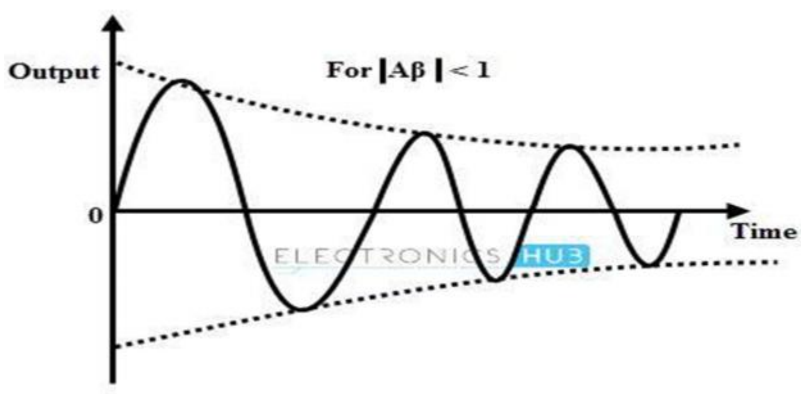
Sustained Oscillations: Sustained oscillations are nothing but oscillations which oscillate with constant amplitude and frequency. Based on the Barkhausen criterion sustained oscillations are produced when the magnitude of loop gain or modulus of A β is equal to one and total phase shift around the loop is 0 degrees or 360 ensuring positive feedback.



Growing Type of Oscillations: If modulus of A β or the magnitude of loop gain is greater than unity and total phase shift around the loop is 0 or 360 degrees, then the oscillations produced by the oscillator are of growing type. The below figure shows the oscillator output with increasing amplitude of oscillations.



Exponentially Decaying Oscillations: If modulus of A β or the magnitude of loop gain is less than unity and total phase shift around the loop is 0 or 360 degrees, then the amplitude of the oscillations decreases exponentially and finally these oscillations will cease.



Classification of oscillators

The oscillators are classified into several types based on various factors like nature of waveform, range of frequency, the parameters used, etc. The following is a broad classification of oscillators.

According to the Waveform Generated

Based on the output waveform, oscillators are classified as sinusoidal oscillators and non-sinusoidal oscillators.

Sinusoidal Oscillators: This type of oscillator generates sinusoidal current or voltages. **Non-sinusoidal Oscillators:** This type of oscillators generates output, which has triangular, square, rectangle, saw tooth waveform or is of pulse shape.

According to the Circuit Components: Depends on the usage of components in the circuit, oscillators are classified into LC, RC and crystal oscillators. The oscillator using inductor and capacitor components is called as LC oscillator while the oscillator using resistance and capacitor components is called as RC oscillators. Also, crystal is used in some oscillators which are called as crystal oscillators.

According to the Frequency Generated: Oscillators can be used to produce the waveforms at frequencies ranging from low to very high levels. Low frequency or audio frequency oscillators are used to generate the oscillations at a range of 20 Hz to 100-200 KHz which is an audio frequency range.

High frequency or radio frequency oscillators are used at the frequencies more than 200-300 KHz up to gigahertz. LC oscillators are used at high frequency range, whereas RC oscillators are used at low frequency range.

Based on the Usage of Feedback

The oscillators consisting of feedback network to satisfy the required conditions of the oscillations are called as feedback oscillators. Whereas the oscillators with absence of feedback network are called as non-feedback type of oscillators. The UJT relaxation oscillator is the example of non-feedback oscillator which uses a negative resistance region of the characteristics of the device.

Some of the sinusoidal oscillators under above categories are

- Tuned-circuits or LC feedback oscillators such as Hartley, Colpitts and Clapp etc.

  RC phase-shift oscillators such as Wein-bridge oscillator.

- Negative-resistance oscillators such as tunnel diode oscillator.

  Crystal oscillators such as Pierce oscillator.

- Heterodyne or beat-frequency oscillator (BFO).

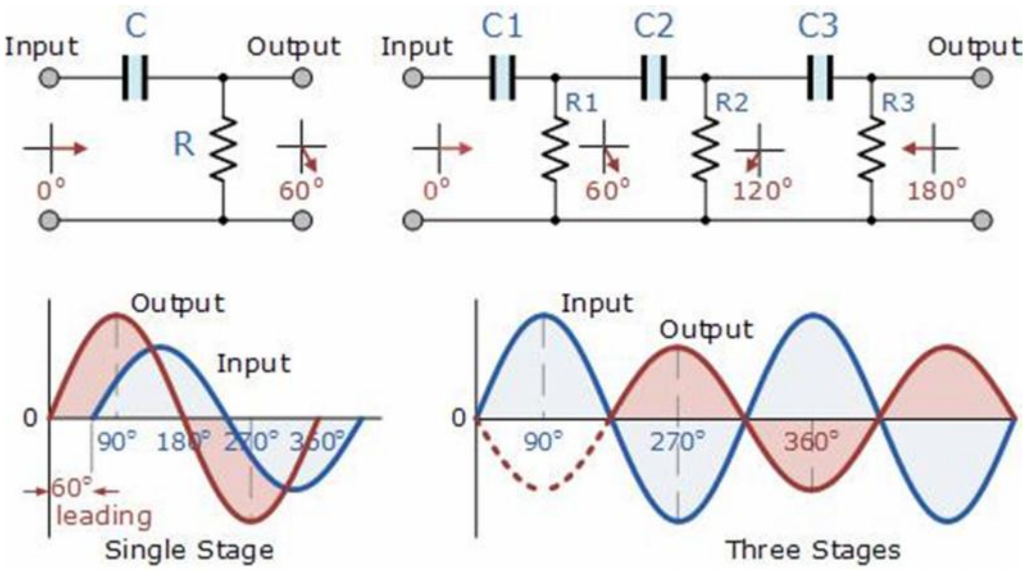
A single stage amplifier will produce 180^{o} of phase shift between its output and input signals when connected in a class-A type configuration.

For an oscillator to sustain oscillations indefinitely, sufficient feedback of the correct phase, that is “Positive Feedback” must be provided along with the transistor amplifier being used acting as an inverting stage to achieve this.

In an **RC Oscillator** circuit the input is shifted 180^{o} through the amplifier stage and 180^{o}again through a second inverting stage giving us “$180^{o} + 180^{o} = 360^{o}$” of phase shift which is effectively the same as 0^{o} thereby giving us the required positive feedback. In other words, the phase shift of the feedback loop should be “0”.

In a **Resistance-Capacitance Oscillator** or simply an **RC Oscillator**, we make use of the fact that a phase shift occurs between the input to a RC network and the output from the same network by using RC elements in the feedback branch, for example.

RC Phase-Shift Network



The circuit on the left shows a single resistor-capacitor network whose output voltage "leads" the input voltage by some angle less than 90^o. An ideal single-pole RC circuit would produce a phase shift of exactly 90^o, and because 180^o of phase shift is required for oscillation, at least two single-poles must be used in an RC oscillator design.

However in reality it is difficult to obtain exactly 90^o of phase shift so more stages are used. The amount of actual phase shift in the circuit depends upon the values of the resistor and the capacitor, and the chosen frequency of oscillations with the phase angle (Φ) being given as:

RC Phase Angle

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

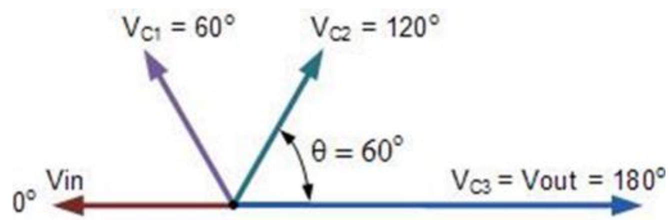
$$Z = \sqrt{R^2 + (X_C)^2}$$

$$\therefore \quad \phi = \tan^{-1}\frac{X_C}{R}$$

Where: X_C is the Capacitive Reactance of the capacitor, R is the Resistance of the resistor, and f is the Frequency.

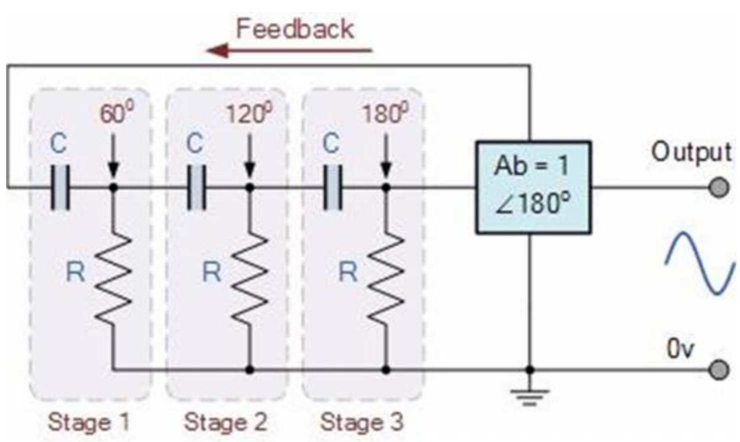
In our simple example above, the values of R and C have been chosen so that at the required frequency the output voltage leads the input voltage by an angle of about 60^o. Then the phase angle between each successive RC section increases by another 60^o giving a phase difference between the input and output of 180^o (3 x 60^o) as shown by the following vector diagram.

Vector Diagram



Then by connecting together three such RC networks in series we can produce a total phase shift in the circuit of 180^o at the chosen frequency and this forms the bases of a “phase shift oscillator” otherwise known as a **RC Oscillator** circuit.

We know that in an amplifier circuit either using a Bipolar Transistor or an Operational Amplifier, it will produce a phase-shift of 180^o between its input and output. If a three-stage RC phase-shift network is connected between this input and output of the amplifier, the total phase shift necessary for regenerative feedback will become 3 x 60^o + 180^o = 360^o as shown.



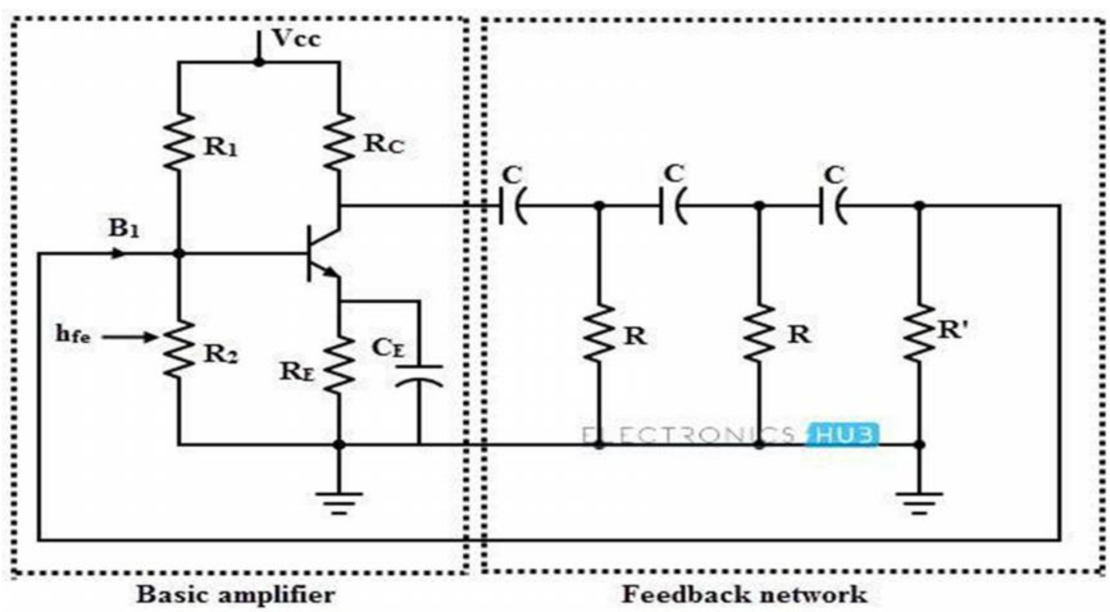
The three RC stages are cascaded together to get the required slope for a stable oscillation frequency. The feedback loop phase shift is -180^o when the phase shift of each stage is -60^o. This occurs when $\omega = 2\pi f = 1.732/RC$ as ($\tan 60^o = 1.732$). Then to achieve the required phase shift in an RC oscillator circuit is to use multiple RC phase-shifting networks such as the circuit below.

RC Phase Shift Oscillator Using BJT

In this transistorized oscillator, a transistor is used as active element of the amplifier stage. The figure below shows the RC oscillator circuit with transistor as active element. The DC operating point in active region of the transistor is established by the resistors R1, R2, RC and RE and the supply voltage Vcc.

The capacitor CE is a bypass capacitor. The three RC sections are taken to be identical and the resistance in the last section is R' = R – hie. The input resistance hie of the transistor is added to R', thus the net resistance given by the circuit is R.

The biasing resistors R1 and R2 are larger and hence no effect on AC operation of the circuit. Also due to negligible impedance offered by the RE – CE combination, it is also no effect on AC operation.



When the power is given to the circuit, noise voltage (which is generated by the electrical components) starts the oscillations in the circuit. A small base current at the transistor amplifier produces a current which is phase shifted by 180 degrees. When this signal is feedback to the input of the amplifier, it will be again phase shifted by 180 degrees. If the loop gain is equal to unity then sustained oscillations will be produced.

By simplifying the circuit with equivalent AC circuit, we get the frequency of oscillations,

$$\mathbf{f = 1/ (2 \pi R C \sqrt{((4Rc / R) + 6)})}$$

If $Rc/R \ll 1$, then

$$f = 1 / (2 \pi R C \sqrt{6})$$

The condition of sustained oscillations,

$$h_{fe}(min) = (4 R_c / R) + 23 + (29 R / R_c)$$

For a phase shift oscillator with R = Rc, hfe should be 56 for sustained oscillations.

From the above equations it is clear that, for changing the frequency of oscillations, R and C values have to be changed.

But for satisfying oscillating conditions, these values of the three sections must be changed simultaneously. So this is not possible in practice, therefore a phase shift oscillator is used as a fixed frequency oscillator for all practical purposes.

Advantages of Phase Shift Oscillators:

- Due to the absence of expensive and bulky high-value inductors, circuit is simple to design and well suited for frequencies below 10 KHz.
- These can produce pure sinusoidal waveform since only one frequency can fulfill the Barkhausen phase shift requirement.
- It is fixed to one frequency.

Disadvantages of Phase Shift Oscillators:

For a variable frequency usage, phase shift oscillators are not suited because the capacitor values will have to be varied. And also, for frequency change in every time requires gain adjustment for satisfying the condition of oscillations.

- These oscillators produce 5% of distortion level in the output.
- This oscillator gives only a small output due to smaller feedback
- These oscillator circuits require a high gain which is practically impossible.

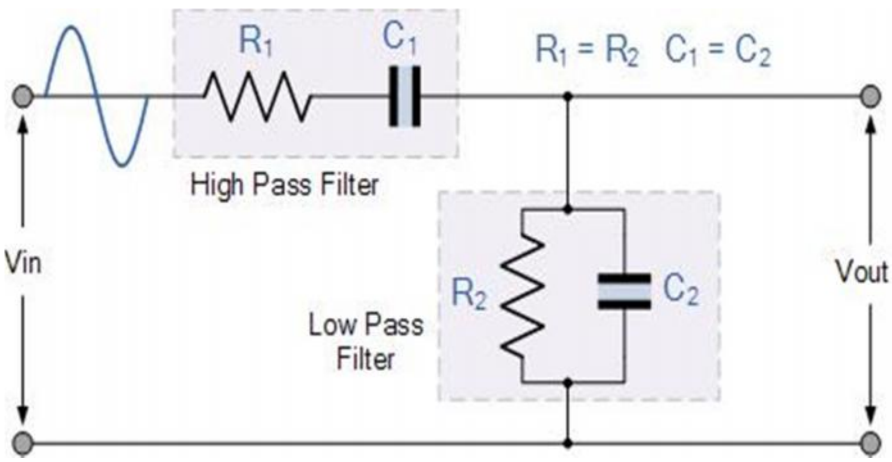
- The frequency stability is poor due to the effect of temperature, aging, etc. of various circuit components.

One of the simplest sine wave oscillators which uses a RC network in place of the conventional LC tuned tank circuit to produce a sinusoidal output waveform, is called a **Wien Bridge Oscillator**.

The **Wien Bridge Oscillator** is so called because the circuit is based on a frequency-selective form of the Wheatstone bridge circuit. The Wien Bridge oscillator is a two-stage RC coupled amplifier circuit that has good stability at its resonant frequency, low distortion and is very easy to tune making it a popular circuit as an audio frequency oscillator but the phase shift of the output signal is considerably different from the previous phase shift **RC Oscillator**.

The **Wien Bridge Oscillator** uses a feedback circuit consisting of a series RC circuit connected with a parallel RC of the same component values producing a phase delay or phase advance circuit depending upon the frequency. At the resonant frequency f_r the phase shift is 0^o. Consider the circuit below.

RC Phase Shift Network

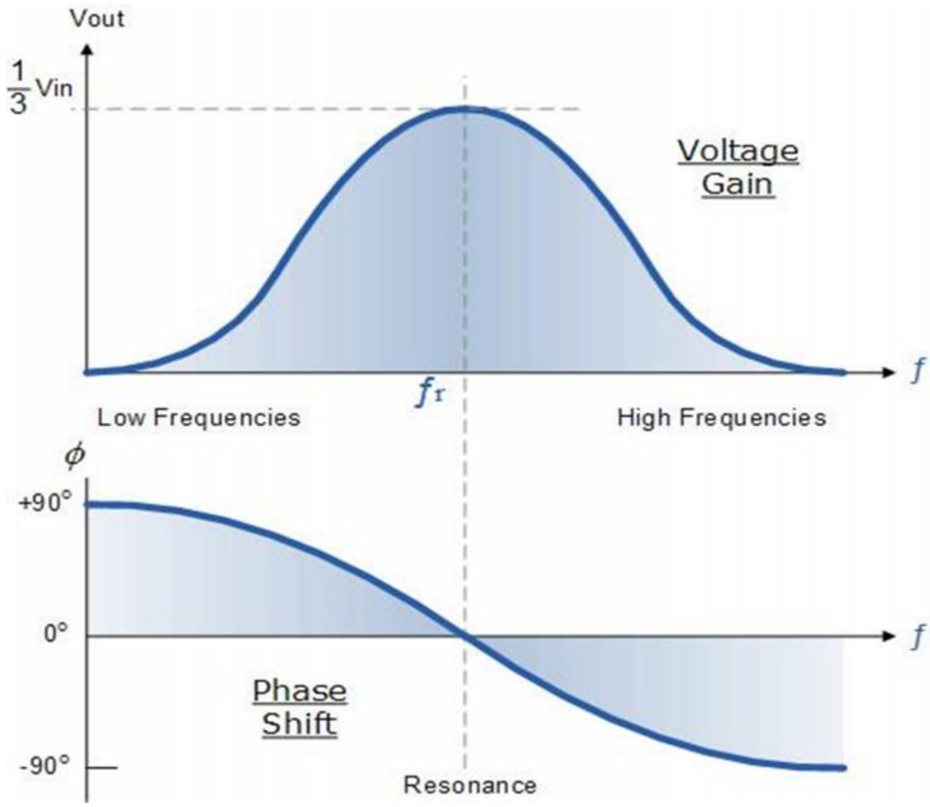


The above RC network consists of a series RC circuit connected to a parallel RC forming basically a **High Pass Filter** connected to a **Low Pass Filter** producing a very selective second-order frequency dependant **Band Pass Filter** with a high Q factor at the selected frequency, fr.

At low frequencies the reactance of the series capacitor (C1) is very high so acts like an open circuit and blocks any input signal at Vin. Therefore there is no output signal, Vout. At high frequencies, the reactance of the parallel capacitor, (C2) is very low so this parallel connected capacitor acts like a short circuit on the output so again there is no output signal. However, between these two extremes the output voltage reaches a maximum value with the frequency at which this happens being called the *Resonant Frequency*, (fr).

At this resonant frequency, the circuits reactance equals its resistance as Xc = R so the phase shift between the input and output equals zero degrees. The magnitude of the output voltage is therefore at its maximum and is equal to one third (1/3) of the input voltage as shown.

Oscillator Output Gain and Phase Shift



It can be seen that at very low frequencies the phase angle between the input and output signals is “Positive” (Phase Advanced), while at very high frequencies the phase angle becomes “Negative” (Phase Delay). In the middle of these two points the circuit is at its resonant frequency, (f_r) with the two signals being “in-phase” or 0^o. We can therefore define this resonant frequency point with the following expression.

Wien Bridge Oscillator Frequency

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

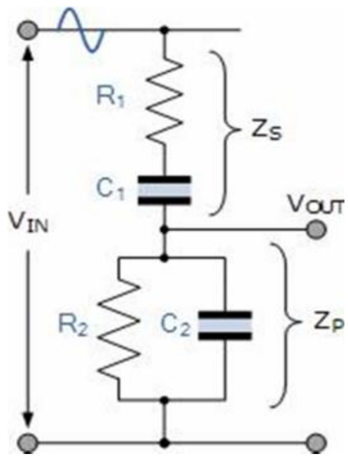
Where:

- f_r is the Resonant Frequency in Hertz
- R is the Resistance in Ohms
- C is the Capacitance in Farads

We said previously that the magnitude of the output voltage, Vout from the RC network is at its maximum value and equal to one third (1/3) of the input voltage, Vin to allow for oscillations to occur. But why one third and not some other value. In order to understand why the output from the RC circuit above needs to be one-third, that is 0.333xVin, we have to consider the complex impedance (Z = R ± jX) of the two connected RC circuits.

We know from our **AC Theory tutorials** that the real part of the complex impedance is the resistance, R while the imaginary part is the reactance, X. As we are dealing with capacitors here, the reactance part will be capacitive reactance, Xc.

The RC Network



If we redraw the above RC network as shown, we can clearly see that it consists of two RC circuits connected together with the output taken from their junction. Resistor R_1 and capacitor C_1 form the top series network, while resistor R_2 and capacitor C_2 form the bottom parallel network.

Therefore the total impedance of the series combination (R_1C_1) we can call, Z_S and the total impedance of the parallel combination (R_2C_2) we can call, Z_P. As Z_S and Z_P are effectively connected together in series across the input, V_{IN}, they form a voltage divider network with the output taken from across $Z_P$as shown.

Let's assume then that the component values of R_1 and R_2 are the same at: 12kΩ,

capacitors C_1 and C_2 are the same at: 3.9nF and the supply frequency, f is 3.4kHz.

Series Circuit

The total impedance of the series combination with resistor, R_1 and capacitor, C_1 is simply:

$$R = 12k\Omega, \quad \text{but} \quad X_C = \frac{1}{2\pi f C}$$

$$\therefore X_C = \frac{1}{2\pi \times 3.4kHz \times 3.9nF} = 12k\Omega$$

$$Z_S = \sqrt{R^2 + X_C^2} = \sqrt{12000^2 + 12000^2}$$

$$\therefore Z_S = 16{,}970\Omega \text{ or } 17k\Omega$$

We now know that with a supply frequency of 3.4kHz, the reactance of the capacitor is the same as the resistance of the resistor at 12kΩ. This then gives us an upper series impedance Z_S of 17kΩ.

For the lower parallel impedance Z_P, as the two components are in parallel, we have to treat this differently because the impedance of the parallel circuit is influenced by this parallel combination.

Parallel Circuit

The total impedance of the lower parallel combination with resistor, R_2 and capacitor, C_2 is given as:

$$R = 12k\Omega, \quad \text{and} \quad X_C = 12k\Omega$$

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{XC} = \frac{1}{12000} + \frac{1}{12000}$$

$$\therefore Z = 6000\Omega \text{ or } 6k\Omega$$

At the supply frequency of 3400Hz, or 3.4KHz, the combined resistance and reactance of the RC parallel circuit becomes 6kΩ (R||Xc) and their parallel impedance is therefore calculated as:

$$R = 6k\Omega, \quad \text{and} \quad X_C = 6k\Omega \quad \text{(Parallel)}$$

$$Z_P = \sqrt{R^2 + X_C^2} = \sqrt{6000^2 + 6000^2}$$

$$\therefore Z_P = 8485\Omega \text{ or } 8.5k\Omega$$

So we now have the value for the series impedance of: 17kΩ's, (Z_S = 17kΩ) and for the parallel impedance of: 8.5kΩ's, (Z_S = 8.5kΩ). Therefore the output impedance, Zout of the voltage divider network at the given frequency is:

$$Z_{OUT} = \frac{Z_P}{Z_P + Z_S} = \frac{8.5k\Omega}{8.5k\Omega + 17k\Omega} = 0.333 \text{ or } \frac{1}{3}$$

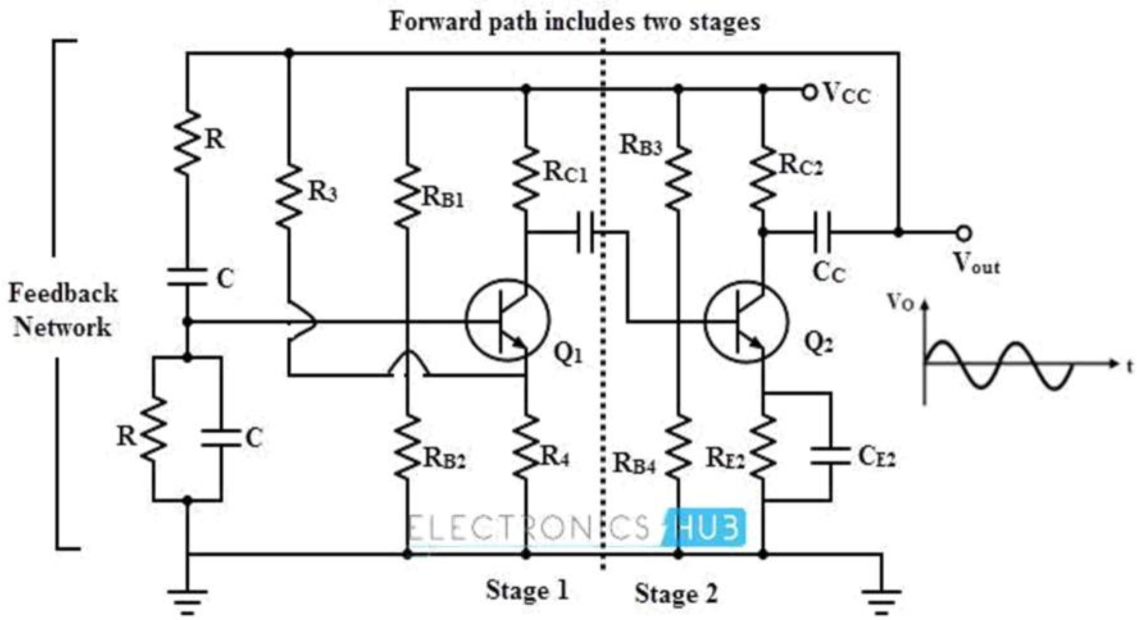
Then at the oscillation frequency, the magnitude of the output voltage, Vout will be equal to Zout x Vin which as shown is equal to one third (1/3) of the input voltage, Vin and it is this frequency selective RC network which forms the basis of the **Wien Bridge Oscillator** circuit.

If we now place this RC network across a non-inverting amplifier which has a gain of 1+R1/R2 the following basic wien bridge oscillator circuit is produced.

Transistorized Wien Bridge Oscillator:

The figure below shows the transistorized Wien bridge oscillator which uses two stage common emitter transistor amplifier. Each amplifier stage introduces a phase shift of 180 degrees and hence a total 360 degrees phase shift is introduced which is nothing but a zero phase shift condition.

The feedback bridge consists of RC series elements, RC parallel elements, R3 and R4 resistances. The input to the bridge circuit is applied from the collector of transistor T2 through a coupling capacitor.



When the DC source is applied to the circuit, a noise signal is at the base of the transistor T1 is generated due to the movement of charge carriers through transistor and other circuit components. This voltage is amplified with gain A and produce output voltage 180 degrees out of phase with input voltage. This output voltage is applied as input to second transistor at base terminal of T2. This voltage is multiplied with gain of the T2. The amplified output of the transistor T2 is 180 degrees out of phase with the output of the T1. This output is feedback to the transistor T1 through the coupling capacitor C. So the oscillations are produced at wide range of frequencies by this positive feedback when Barkhausen conditions are satisfied. Generally, the

Wien bridge in the feedback network incorporates the oscillations at single desired frequency. The bridge is get balanced at the frequency at which total phase shift is zero.

The output of the two stage transistor acts as an input to the feedback network which is applied

between the base and ground.

Feedback voltage,

$$V_f = (V_o \times R_4) / (R_3 + R_4)$$

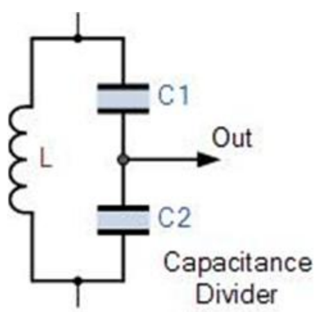
Advantages:

- Because of the usage of two stage amplifier, the overall gain of this oscillator is high.
- By varying the values of C1 and C2 or with use of variable resistors, the frequency of oscillations can be varied.
- It produces a very good sine wave with less distortion
- The frequency stability is good.
- Due to the absence of inductors, no interference occurs from external magnetic fields.

Disadvantages:

- More number of components is needed for two stage amplifier type of Wien bridge oscillators.
- Very high frequencies cannot be generated.

In many ways, the Colpitts oscillator is the exact opposite of the **Hartley Oscillator** we looked at in the previous tutorial. Just like the Hartley oscillator, the tuned tank circuit consists of an LC resonance sub-circuit connected between the collector and the base of a single stage transistor amplifier producing a sinusoidal output waveform. The basic configuration of the **Colpitts Oscillator** resembles that of the *Hartley Oscillator* but the difference this time is that the centre tapping of the tank sub-circuit is now made at the junction of a "capacitive voltage divider" network instead of a tapped autotransformer type inductor as in the Hartley oscillator. Related Products: Oscillators and Crystals | Controlled Oscillator | MEMS Oscillators | Oscillator Misc | Silicon Oscillators

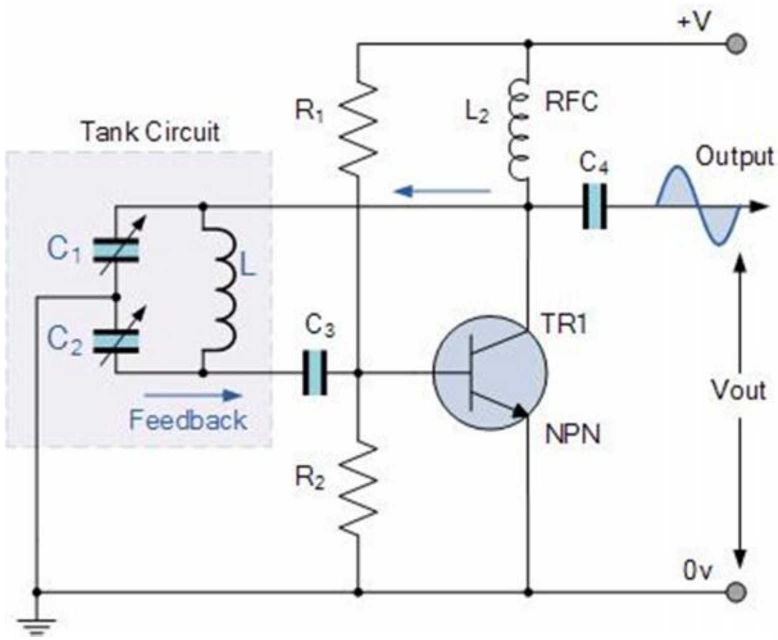


Colpitts Oscillator:

Tank Circuit:

The Colpitts oscillator uses a capacitive voltage divider network as its feedback source. The two capacitors, C1 and C2 are placed across a single common inductor, L as shown. Then C1, C2 and L form the tuned tank circuit with the condition for oscillations being: $X_{C1} + X_{C2} = X_L$, the same as for the Hartley oscillator circuit. The advantage of this type of capacitive circuit configuration is that with less self and mutual inductance within the tank circuit, frequency stability of the oscillator is improved along with a more simple design. As with the Hartley oscillator, the Colpitts oscillator uses a single stage bipolar transistor amplifier as the gain element which produces a sinusoidal output. Consider the circuit below.

Basic Colpitts Oscillator Circuit



The emitter terminal of the transistor is effectively connected to the junction of the two capacitors, C1 and C2 which are connected in series and act as a simple voltage divider. When the power supply is firstly applied, capacitors C1 and C2 charge up and then discharge through the coil L. The oscillations across the capacitors are applied to the base-emitter junction and appear in the amplified at the collector output.

Resistors, R1 and R2 provide the usual stabilizing DC bias for the transistor in the normal manner while the additional capacitors act as a DC-blocking bypass capacitors. A radio-frequency choke (RFC) is used in the collector circuit to provide a high reactance (ideally open circuit) at the frequency of oscillation, (fr) and a low resistance at DC to help start the oscillations.

The required external phase shift is obtained in a similar manner to that in the Hartley oscillator circuit with the required positive feedback obtained for sustained undamped oscillations. The amount of feedback is determined by the ratio of C1 and C2. These two capacitances are generally “ganged” together to provide a constant amount of feedback so that as one is adjusted the other automatically follows.

The frequency of oscillations for a Colpitts oscillator is determined by the resonant frequency of the LC tank circuit and is given as:

$$f_r = \frac{1}{2\pi\sqrt{L C_T}}$$

Where C_T is the capacitance of C1 and C2 connected in series and is given as:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \quad \text{or} \quad C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

The configuration of the transistor amplifier is of a **Common Emitter Amplifier** with the output signal 180^o out of phase with regards to the input signal. The additional 180^ophase shift require for oscillation is achieved by the fact that the two capacitors are connected together in series but in parallel with the inductive coil resulting in overall phase shift of the circuit being zero or 360^o. The amount of feedback depends on the values of C1 and C2. We can see that the voltage across C1 is the the same as the oscillators output voltage, Vout and that the voltage across C2 is the oscillators feedback voltage. Then the voltage across C1 will be much greater than that across C2.

Therefore, by changing the values of capacitors, C1 and C2 we can adjust the amount of feedback voltage returned to the tank circuit. However, large amounts of feedback may cause the output sine wave to become distorted, while small amounts of feedback may not allow the circuit to oscillate.

Then the amount of feedback developed by the Colpitts oscillator is based on the capacitance ratio of C1 and C2 and is what governs the the excitation of the oscillator. This ratio is called the “feedback fraction” and is given simply as:

$$\text{Feedback Fraction} = \frac{C_1}{C_2}\,\%$$

Colpitts Oscillator Example :

A Colpitts Oscillator circuit having two capacitors of 24nF and 240nF respectively are connected in parallel with an inductor of 10mH. Determine the frequency of oscillations of the circuit, the feedback fraction and draw the circuit.

The oscillation frequency for a Colpitts Oscillator is given as:

$$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$

As the colpitts circuit consists of two capacitors in series, the total capacitance is therefore:

$$C_T = \frac{24nF \times 240nF}{24nF + 240nF} = 21.82nF$$

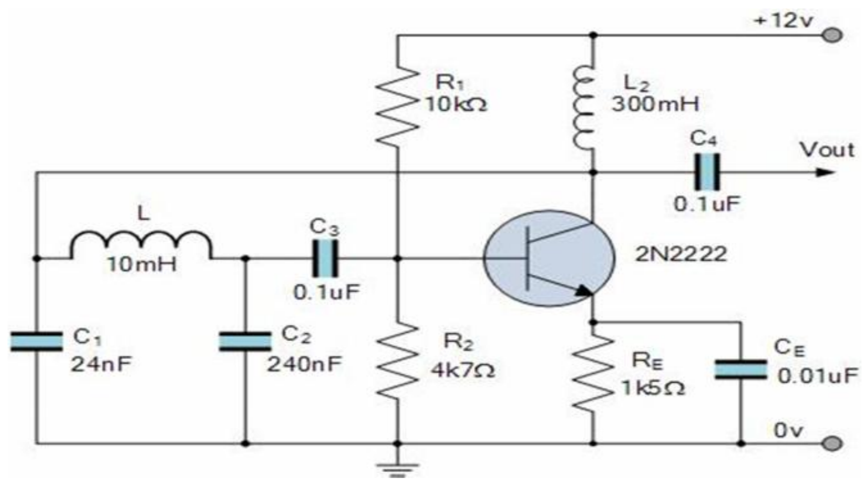
The inductance of the inductor is given as 10mH, then the frequency of oscillation is:

$$f_r = \frac{1}{2\pi\sqrt{LC_T}} = \frac{1}{6.283\sqrt{0.01 \times 21.82 \times 10^{-9}}} = 10.8kHz$$

The frequency of oscillations for the Colpitts Oscillator is therefore 10.8kHz with the feedback fraction given as:

$$F_F = \frac{C_1}{C_2} = \frac{24nF}{240nF} = 10\%$$

Colpitts Oscillator Circuit:



Colpitts Oscillator Summary:

Then to summaries, the Colpitts Oscillator consists of a parallel LC resonator tank circuit whose feedback is achieved by way of a capacitive divider. Like most oscillator circuits, the Colpitts oscillator exists in several forms, with the most common form being the transistor circuit above.

The centre tapping of the tank sub-circuit is made at the junction of a "capacitive voltage divider" network to feed a fraction of the output signal back to the emitter of the transistor. The two capacitors in series produce a 180^o phase shift which is inverted by another 180^o to produce the required positive feedback. The oscillating frequency which is a purer sine-wave voltage is determined by the resonance frequency of the tank circuit.

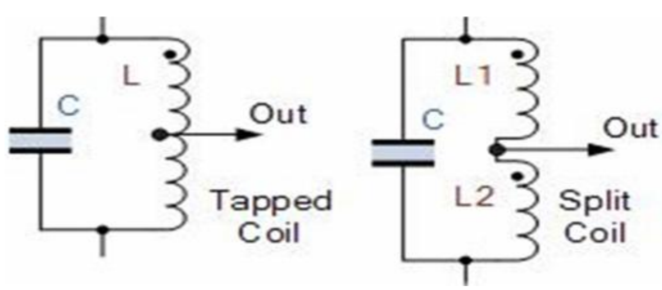
Applications of Colpitts oscillator

- Colpitts oscillators are used for high frequency range and high frequency stability
- A surface acoustical wave (SAW) resonator
- Microwave applications
- Mobile and communication systems
- These are used in chaotic circuits which are capable to generate oscillations from audio frequency range to the optical band. These application areas include broadband communications, spectrum spreading, signal masking, etc.

One of the main disadvantages of the basic LC Oscillator circuit we looked at in the previous tutorial is that they have no means of controlling the amplitude of the oscillations and also, it is difficult to tune the oscillator to the required frequency. If the cumulative electromagnetic coupling between L_1 and L_2 is too small there would be insufficient feedback and the oscillations would eventually die away to zero.

Likewise if the feedback was too strong the oscillations would continue to increase in amplitude until they were limited by the circuit conditions producing signal distortion. So it becomes very difficult to "tune" the oscillator. However, it is possible to feed back exactly the right amount of voltage for constant amplitude oscillations. If we feed back more than is necessary the amplitude of the oscillations can be controlled by biasing the amplifier in such a way that if the oscillations increase in amplitude, the bias is increased and the gain of the amplifier is reduced. If the amplitude of the oscillations decreases the bias decreases and the gain of the amplifier increases, thus increasing the feedback. In this way the amplitude of the oscillations are kept constant using a process known as Automatic Base Bias**.**

One big advantage of automatic base bias in a voltage controlled oscillator, is that the oscillator can be made more efficient by providing a Class-B bias or even a Class-C bias condition of the transistor. This has the advantage that the collector current only flows during part of the oscillation cycle so the quiescent collector current is very small. Then this "self-tuning" base oscillator circuit forms one of the most common types of LC parallel resonant feedback oscillator configurations called the **Hartley Oscillator** circuit.



Hartley Oscillator Tank Circuit:

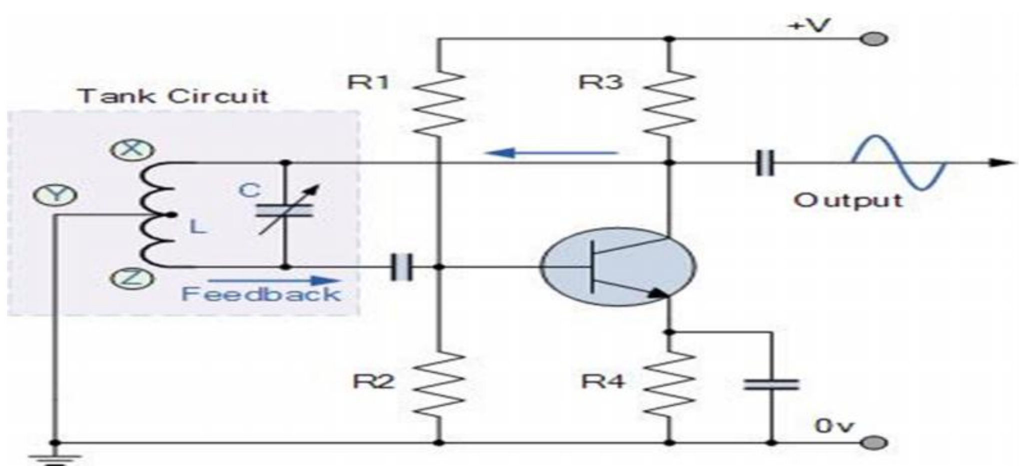
In the **Hartley Oscillator** the tuned LC circuit is connected between the collector and the base of a transistor amplifier. As far as the oscillatory voltage is concerned, the emitter is connected to a tapping point on the tuned circuit coil.

The feedback part of the tuned LC tank circuit is taken from the centre tap of the inductor coil or even two separate coils in series which are in parallel with a variable capacitor, C as shown.

The Hartley circuit is often referred to as a split-inductance oscillator because coil L is centre-tapped. In effect, inductance L acts like two separate coils in very close proximity with the current flowing through coil section XY induces a signal into coil section YZ below.

An Hartley Oscillator circuit can be made from any configuration that uses either a single tapped coil (similar to an autotransformer) or a pair of series connected coils in parallel with a single capacitor as shown below.

Basic Hartley Oscillator Design



When the circuit is oscillating, the voltage at point X (collector), relative to point Y (emitter), is 180^{o} out-of-phase with the voltage at point Z (base) relative to point Y. At the frequency of oscillation, the impedance of the Collector load is resistive and an increase in Base voltage causes a decrease in the Collector voltage.

Then there is a 180^{o} phase change in the voltage between the Base and Collector and this along with the original 180^{o} phase shift in the feedback loop provides the correct phase relationship of positive feedback for oscillations to be maintained.

The amount of feedback depends upon the position of the “tapping point” of the inductor. If this is moved nearer to the collector the amount of feedback is increased, but the output taken between the Collector and earth is reduced and vice versa. Resistors, R1 and R2 provide the usual stabilizing DC bias for the transistor in the normal manner while the capacitors act as DC-blocking capacitors.

In this **Hartley Oscillator** circuit, the DC Collector current flows through part of the coil and for this reason the circuit is said to be "Series-fed" with the frequency of oscillation of the Hartley Oscillator being given as.

$$f = \frac{1}{2\pi\sqrt{L_T C}}$$

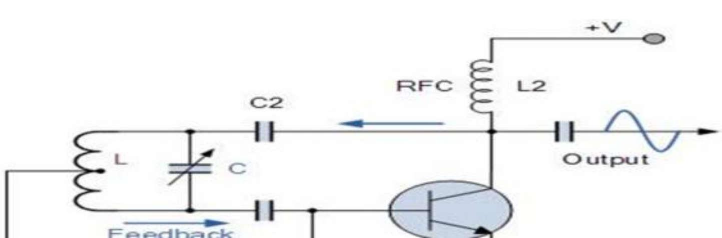
where: $L_T = L_1 + L_2 + 2M$

Note: L_T is the total cumulatively coupled inductance if two separate coils are used including their mutual inductance, M.

The frequency of oscillations can be adjusted by varying the "tuning" capacitor, C or by varying the position of the iron-dust core inside the coil (inductive tuning) giving an output over a wide range of frequencies making it very easy to tune. Also the **Hartley Oscillator** produces an output amplitude which is constant over the entire frequency range.

As well as the Series-fed Hartley Oscillator above, it is also possible to connect the tuned tank circuit across the amplifier as a shunt-fed oscillator as shown below.

Shunt-fed Hartley Oscillator Circuit:



In the shunt-fed Hartley oscillator circuit, both the AC and DC components of the Collector current have separate paths around the circuit. Since the DC component is blocked by the capacitor, C2 no DC flows through the inductive coil, L and less power is wasted in the tuned circuit.

The Radio Frequency Coil (RFC), L2 is an RF choke which has a high reactance at the frequency of oscillations so that most of the RF current is applied to the LC tuning tank circuit via capacitor, C2 as the DC component passes through L2 to the power supply. A resistor could be used in place of the RFC coil, L2 but the efficiency would be less.

Hartley Oscillator Example

A Hartley Oscillator circuit having two individual inductors of 0.5mH each, are designed to resonate in parallel with a variable capacitor that can be adjusted between 100pF and 500pF. Determine the upper and lower frequencies of oscillation and also the Hartley oscillators bandwidth.

From above we can calculate the frequency of oscillations for a Hartley Oscillator as:

$$f_r = \frac{1}{2\pi\sqrt{L_T C}}$$

The circuit consists of two inductive coils in series, so the total inductance is given as:

$$L_T = L_1 + L_2 = 0.5\text{mH} + 0.5\text{mH} = 1.0\text{mH}$$

Hartley Oscillator Upper Frequency

$$f_H = \frac{1}{2\pi\sqrt{1mH \times 100pF}} = \frac{1}{6.283\sqrt{1\times10^{-13}}} = 503228Hz$$

$$\therefore f_H = 503kHz$$

Hartley Oscillator Lower Frequency

$$f_L = \frac{1}{2\pi\sqrt{1mH \times 500pF}} = \frac{1}{6.283\sqrt{5\times10^{-13}}} = 225050Hz$$

$$\therefore f_L = 225kHz$$

Hartley Oscillator Bandwidth

$$\text{Bandwidth} = f_H - f_L$$

$$= 503 - 225 = 278kHz$$

Mutual Inductance in Hartley Oscillator:

The change in current through coil induces the current in other vicinity coil by the magnetic field is called as mutual inductance. It is an additional amount of inductance caused in one inductor due to the magnetic flux of other inductor. By considering the effect of mutual inductance, the total inductance of the coils can be calculated by the formula given below.

$$Leq = L1 + L2 + 2M$$

Where M is the mutual inductance and its value depends on the effective coupling between the inductors, spacing between them, dimensions of each coil, number of turns in each coil and type of material used for the common core. In radio frequency oscillators, depending on the North and south polarities of the fields generated by the closely coupled inductors, the total inductance of the circuit is determined. If the fields generated by the individual coils are in the same direction, then the mutual inductance will add to the total inductance, hence the total inductance is increased. If the fields are in opposite direction, then the mutual inductance will reduce the total inductance. Therefore, the oscillator working frequency will be increased.

The design of the Hartley oscillator considers this mutual effect of the two inductors. In practical, a common core is used for both inductors, however depending on the coefficient of coupling the mutual inductance effect can be much greater. This coefficient value is unity when there is hundred percent magnetic coupling between the inductors and its value is zero if there is no magnetic coupling between the inductors.

The Hartley Oscillator Summary:

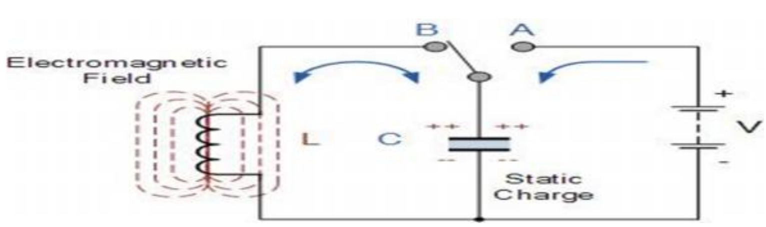
Then to summarize, the Hartley Oscillator consists of a parallel LC resonator tank circuit whose feedback is achieved by way of an inductive divider. Like most oscillator circuits, the Hartley oscillator exists in several forms, with the most common form being the transistor circuit above.

This *Hartley Oscillator* configuration has a tuned tank circuit with its resonant coil tapped to feed a fraction of the output signal back to the emitter of the transistor. Since the output of the transistors emitter is always "in-phase" with the output at the collector, this feedback signal is positive. The oscillating frequency which is a sine-wave voltage is determined by the resonance frequency of the tank circuit.

In the next tutorial about Oscillators, we will look at another type of LC oscillator circuit that is the opposite to the Hartley oscillator called the Colpitts oscillator. The Colpitts oscillator uses two capacitors in series to form a centre tapped capacitance in parallel with a single inductance within its resonant tank circuit.

When a constant voltage but of varying frequency is applied to a circuit consisting of an inductor, capacitor and resistor the reactance of both the Capacitor/Resistor and Inductor/Resistor circuits is to change both the amplitude and the phase of the output signal as compared to the input signal due to the reactance of the components used. At high frequencies the reactance of a capacitor is very low acting as a short circuit while the reactance of the inductor is high acting as an open circuit. At low frequencies the reverse is true, the reactance of the capacitor acts as an open circuit and the reactance of the inductor acts as a short circuit. Between these two extremes the combination of the inductor and capacitor produces a "Tuned" or "Resonant" circuit that has a **Resonant Frequency**, (f_r) in which the capacitive and inductive reactance's are equal and cancel out each other, leaving only the resistance of the circuit to oppose the flow of current. This means that there is no phase shift as the current is in phase with the voltage. Consider the circuit below.

Basic LC Oscillator Tank Circuit:



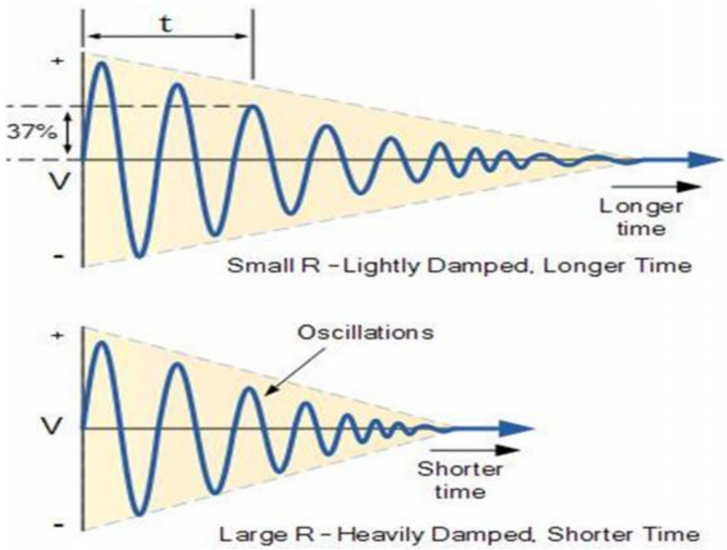
The circuit consists of an inductive coil, L and a capacitor, C. The capacitor stores energy in the form of an electrostatic field and which produces a potential (*static voltage*) across its plates, while the inductive coil stores its energy in the form of an electromagnetic field. The capacitor is charged up to the DC supply voltage, V by putting the switch in position A.

When the capacitor is fully charged the switch changes to position B. The charged capacitor is now connected in parallel across the inductive coil so the capacitor begins to discharge itself through the coil. The voltage across C starts falling as the current through the coil begins to rise. This rising current sets up an electromagnetic field around the coil which resists this flow of current. When the capacitor, C is completely discharged the energy that was originally stored in the capacitor, C as an electrostatic field is now stored in the inductive coil, L as an electromagnetic field around the coils windings. As there is now no external voltage in the circuit to maintain the current within the coil, it starts to fall as the electromagnetic field begins to collapse. A back emf is induced in the coil ($e = -Ldi/dt$) keeping the current flowing in the original direction. These current charges up capacitor, C with the opposite polarity to its original charge. C continues to charge up until the current reduces to zero and the electromagnetic field of the coil has collapsed completely.

The energy originally introduced into the circuit through the switch, has been returned to the capacitor which again has an electrostatic voltage potential across it, although it is now of the opposite polarity. The capacitor now starts to discharge again back through the coil and the whole process is repeated. The polarity of the voltage changes as the energy is passed back and forth between the capacitor and inductor producing an AC type sinusoidal voltage and current waveform. This process then forms the basis of an LC oscillators tank circuit and theoretically this cycling back and forth will continue indefinitely.

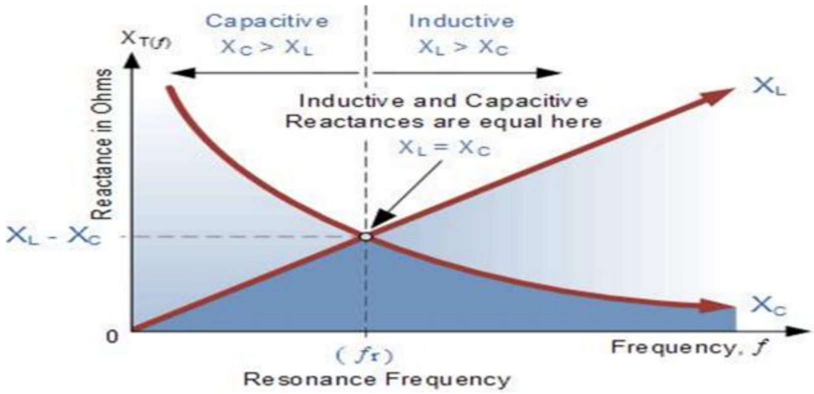
However, things are not perfect and every time energy is transferred from the capacitor, C to inductor, L and back from L to C some energy losses occur which decay the oscillations to zero over time. This oscillatory action of passing energy back and forth between the capacitor, C to the inductor, L would continue indefinitely if it was not for energy losses within the circuit. Electrical energy is lost in the DC or real resistance of the inductors coil, in the dielectric of the capacitor, and in radiation from the circuit so the oscillation steadily decreases until they die away completely and the process stops. Then in a practical LC circuit the amplitude of the oscillatory voltage decreases at each half cycle of oscillation and will eventually die away to zero. The oscillations are then said to be “damped” with the amount of damping being determined by the quality or Q-factor of the circuit.

Damped Oscillations



The frequency of the oscillatory voltage depends upon the value of the inductance and capacitance in the LC tank circuit. We now know that for *resonance* to occur in the tank circuit, there must be a frequency point were the value of X_C, the capacitive reactance is the same as the value of X_L, the inductive reactance ($X_L = X_C$) and which will therefore cancel out each other out leaving only the DC resistance in the circuit to oppose the flow of current. If we now place the curve for inductive reactance of the inductor on top of the curve for capacitive reactance of the capacitor so that both curves are on the same frequency axes, the point of intersection will give us the resonance frequency point, (f_r or ω_r) as shown below.

Resonance Frequency



Where: f_r is in Hertz, L is in Henries and C is in Farads. Then the frequency at which this will happen is given as:

$$X_L = 2\pi f L \quad \text{and} \quad X_C = \frac{1}{2\pi f C}$$

$$\text{at resonance:} \quad X_L = X_C$$

$$\therefore \; 2\pi f L = \frac{1}{2\pi f C}$$

$$2\pi f^2 L = \frac{1}{2\pi C}$$

$$\therefore \; f^2 = \frac{1}{(2\pi)^2 LC}$$

$$f = \frac{\sqrt{1}}{\sqrt{(2\pi)^2 LC}}$$

Then by simplifying the above equation we get the final equation for **Resonant Frequency**, f_r in a tuned LC circuit as:

Resonant Frequency of a LC Oscillator:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Where:

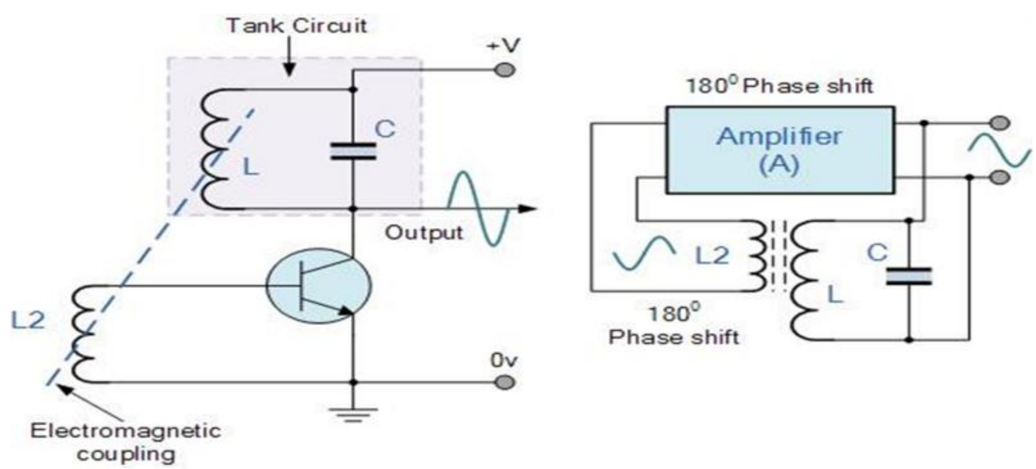
- L is the Inductance in Henries
- C is the Capacitance in Farads
- f_r is the Output Frequency in Hertz

This equation shows that if either L or C are decreased, the frequency increases. This output frequency is commonly given the abbreviation of (f_r) to identify it as the “resonant frequency”.To keep the oscillations going in an LC tank circuit, we have to replace all the energy lost in each oscillation and also maintain the amplitude of these oscillations at a constant level. The amount of energy replaced must therefore be equal to the energy lost during each cycle.

If the energy replaced is too large the amplitude would increase until clipping of the supply rails occurs. Alternatively, if the amount of energy replaced is too small the amplitude would eventually decrease to zero over time and the oscillations would stop. The simplest way of replacing this lost energy is to take part of the output from the LC tank circuit, amplify it and then feed it back into the LC circuit again. This process can be achieved using a voltage amplifier using an op-amp, FET or bipolar transistor as its active device. However, if the loop gain of the feedback amplifier is too small, the desired oscillation decays to zero and if it is too large, the waveform becomes distorted.

To produce a constant oscillation, the level of the energy fed back to the LC network must be accurately controlled. Then there must be some form of automatic amplitude or gain control when the amplitude tries to vary from a reference voltage either up or down.To maintain a stable oscillation the overall gain of the circuit must be equal to one or unity. Any less and the oscillations will not start or die away to zero, any more the oscillations will occur but the amplitude will become clipped by the supply rails causing distortion. Consider the circuit below.

Basic Transistor LC Oscillator Circuit



A **Bipolar Transistor** is used as the LC oscillator's amplifier with the tuned LC tank circuit acts as the collector load. Another coil L2 is connected between the base and the emitter of the transistor whose electromagnetic field is "mutually" coupled with that of coil L.

“Mutual inductance” exists between the two circuits and the changing current flowing in one coil circuit induces, by electromagnetic induction, a potential voltage in the other (transformer effect) so as the oscillations occur in the tuned circuit, electromagnetic energy is transferred from coil L to coil L2 and a voltage of the same frequency as that in the tuned circuit is applied between the base and emitter of the transistor. In this way the necessary automatic feedback voltage is applied to the amplifying transistor.

The amount of feedback can be increased or decreased by altering the coupling between the two coils L and L2. When the circuit is oscillating its impedance is resistive and the collector and base voltages are 180^{o} out of phase. In order to maintain oscillations (called frequency stability) the voltage applied to the tuned circuit must be “in-phase” with the oscillations occurring in the tuned circuit.

Therefore, we must introduce an additional 180^{o} phase shift into the feedback path between the collector and the base. This is achieved by winding the coil of L2 in the correct direction relative to coil L giving us the correct amplitude and phase relationships for the **Oscillators** circuit or by connecting a phase shift network between the output and input of the amplifier. The **LC Oscillator** is therefore a “Sinusoidal Oscillator” or a “Harmonic Oscillator” as it is more commonly called. LC oscillators can generate high frequency sine waves for use in radio frequency (RF) type applications with the transistor amplifier being of a Bipolar Transistor or FET.

Harmonic Oscillators come in many different forms because there are many different ways to construct an LC filter network and amplifier with the most common being the **Hartley LC Oscillator**, **Colpitts LC Oscillator**, **Armstrong Oscillator** and **Clapp Oscillator** to name a few.

LC Oscillator Example:

An inductance of 200mH and a capacitor of 10pF are connected together in parallel to create an LC oscillator tank circuit. Calculate the frequency of oscillation.

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{200\text{mH} \times 10\text{pF}}} = 112.5\ \text{kHz}$$

Then we can see from the above example that by decreasing the value of either the capacitance, C or the inductance, L will have the effect of increasing the frequency of oscillation of the LC tank circuit.

LC Oscillators Summary:

The basic conditions required for an **LC oscillator** resonant tank circuit are given as follows.

- For oscillations to exist an oscillator circuit MUST contain a reactive (frequency-dependant) component either an "Inductor", (L) or a "Capacitor", (C) as well as a DC power source.
- In a simple inductor-capacitor, LC circuit, oscillations become damped over time due to component and circuit losses.
- Voltage amplification is required to overcome these circuit losses and provide positive gain.
- The overall gain of the amplifier must be greater than one, unity.
- Oscillations can be maintained by feeding back some of the output voltage to the tuned circuit that is of the correct amplitude and in-phase, (0^o).
- Oscillations can only occur when the feedback is "Positive" (self-regeneration).
- The overall phase shift of the circuit must be zero or 360^o so that the output signal from the feedback network will be "in-phase" with the input signal.