Subject Name: **Industrial Electronics**

Subject Code: **EC-5005**

Semester: **5th**

Unit IV

Applications of OP-AMP Basics of OP-AMP, relaxation oscillator, window comparator, Op-comp as rectangular to triangular pulse converter and vice- versa, Wien bridge oscillator, function generator, frequency response of OP-AMP, simplified circuit diagram of OP-AMP, power supplies using OP-AMP, filters (low-pass, high pass) using OP-AMP.

Basics of OP-AMP

An operational amplifier is a direct coupled amplifier with high voltage gain. It normally consists of one or more differential amplifier stages followed by level shifting stage and an output stage. The name operational amplifier has been derived from the original usage for mathematical operations.

Symbol

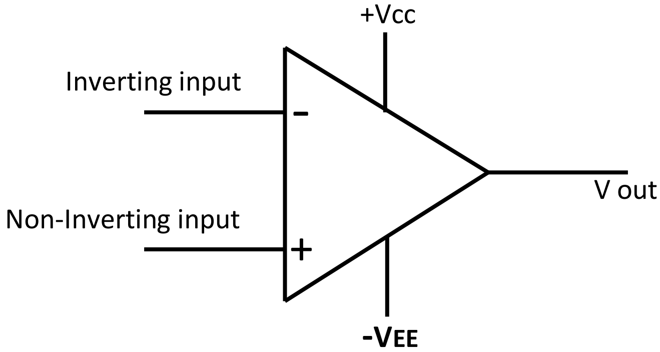


Figure 1 Symbolic representation

Properties of op amp

An ideal op-amp is usually considered to have the following properties:

- Infinite open-loop gain
- Infinite voltage range available at the output
- Infinite bandwidth with zero phase shift and infinite slew rate
- Infinite input impedance and so zero input current and zero input offset voltage
- Zero output impedance
- Infinite Common-mode rejection ratio (CMRR)

Relaxation oscillator

Figure 2 shows the circuit diagram of Relaxation oscillator whose output frequency depends on charging and discharging of capacitor. In this circuit no any input signal is applied. The circuit generates a rectangular wave as an output. Assuming that the output is in positive saturation $+V_{sat}$ .The voltage at the non-inverting input becomes V_{ut}. The capacitor charges exponentially towards $+V_{sat}$. As soon as capacitor voltage reaches just above a threshold voltage V_{ut}, then the output switches to $-V_{sat}$. Now a negative voltage V_{lt} is fed back to the non inverting terminal through the potential divider circuit. So the capacitor discharges from V_{ut} to zero. Completely and recharges towards $-V_{sat}$ in reverse direction as shown in figure 3.When the capacitor C_T reaches just below the threshold voltage V_{lt}, then the output switches back to $+V_{sat}$. Because of continuous charging and discharging of the capacitor, the output obtained is rectangular waveform having the duty cycle of 50%.

The time period of rectangular wave is expressed by:

$$T = 2R_T C_T ln\left(\frac{1+k}{1-k}\right)$$

Where

$k = \frac{R_2}{R_1+R_2}$, feedback fraction

The frequency of the output rectangular wave is expressed by:

$$f = \frac{1}{T}$$

If the value of the time constant $R_T C_T$ is increased, it takes longer for the capacitor voltage to reach V_{ut} or V_{lt}.

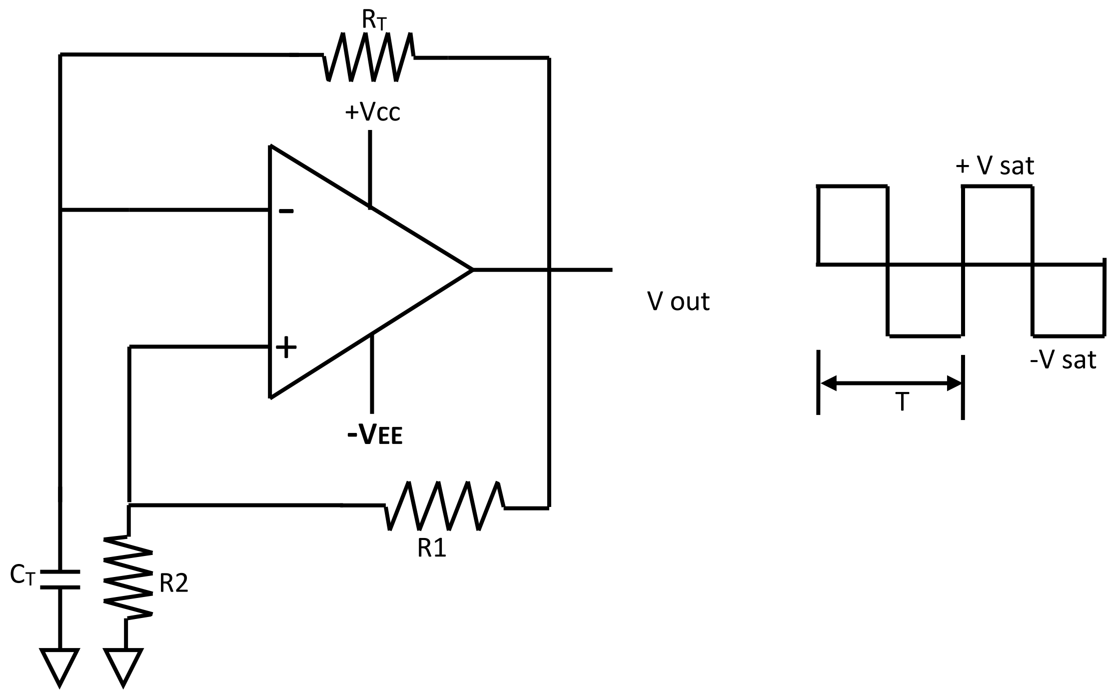


Figure 2 Circuit diagram of Relaxation oscillator

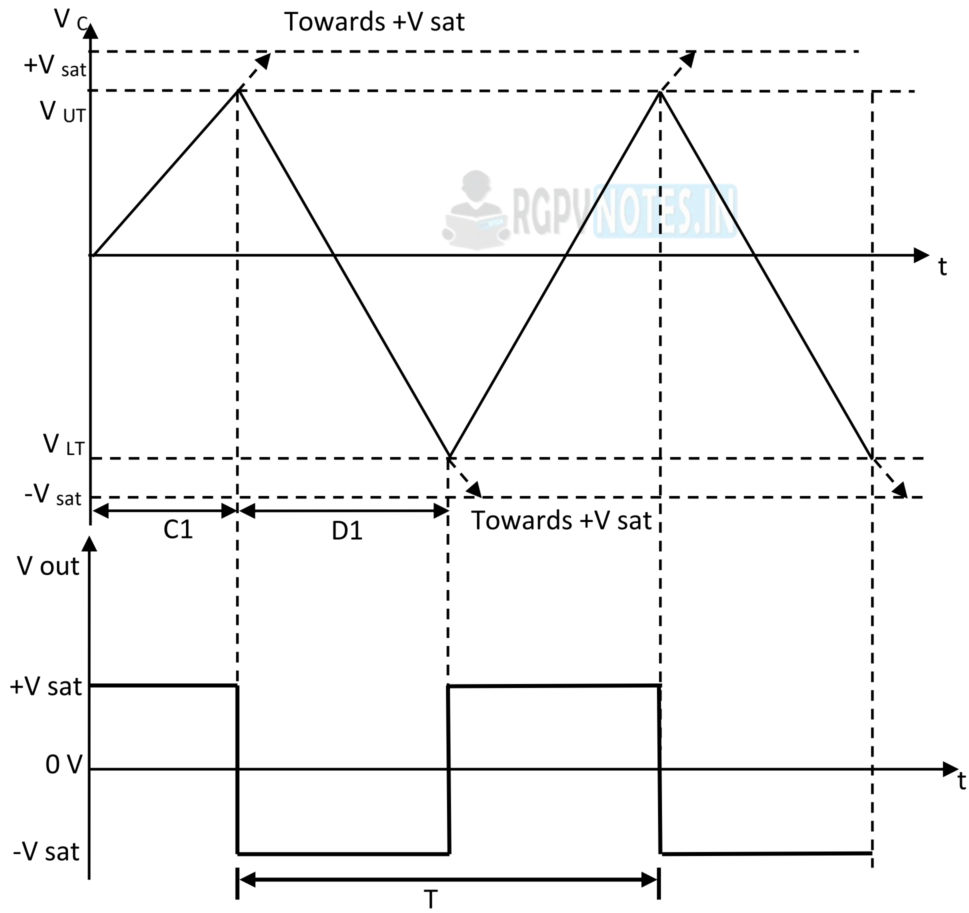


Figure 3 Capacitor voltage and output voltage waveform of relaxation oscillator

Window comparator

Figure 4 shows the circuit of window comparator using operational amplifier which is a dual comparator circuit named as upper comparator and lower comparator and produces a two-state output that indicates whether or not the input voltage is between the limits established by the V ref voltages of both comparators. It is frequently used to sound an alarm when a measured variable goes outside of a preset range. The reference voltages in figure are established by two diode circuits.

To examine the operation of the circuit, let us start by assuming that the input voltage is within the window. That is, the input voltage is less than +V ref and greater than-V ref. Under these conditions, the outputs of both op amps will be driven to the +V sat level. This reverse-biases the two isolation diodes (D1 and D2) and allows the output (V o) to rise to +15 volts, indicating an "in window" condition.

Now suppose that the input either exceeds + V ref or falls below –V ref. In either of these cases, the output of one of the two operational amplifiers will go to the –V sat level and forward-bias its associated isolation diode. This will cause the output of the circuit (V o) to be pulled to-15 volts. In practice, the output voltage will be equal to the negative saturation level plus the forward voltage drop of the conducting isolation diode. This negative level indicates an "out of window" condition.

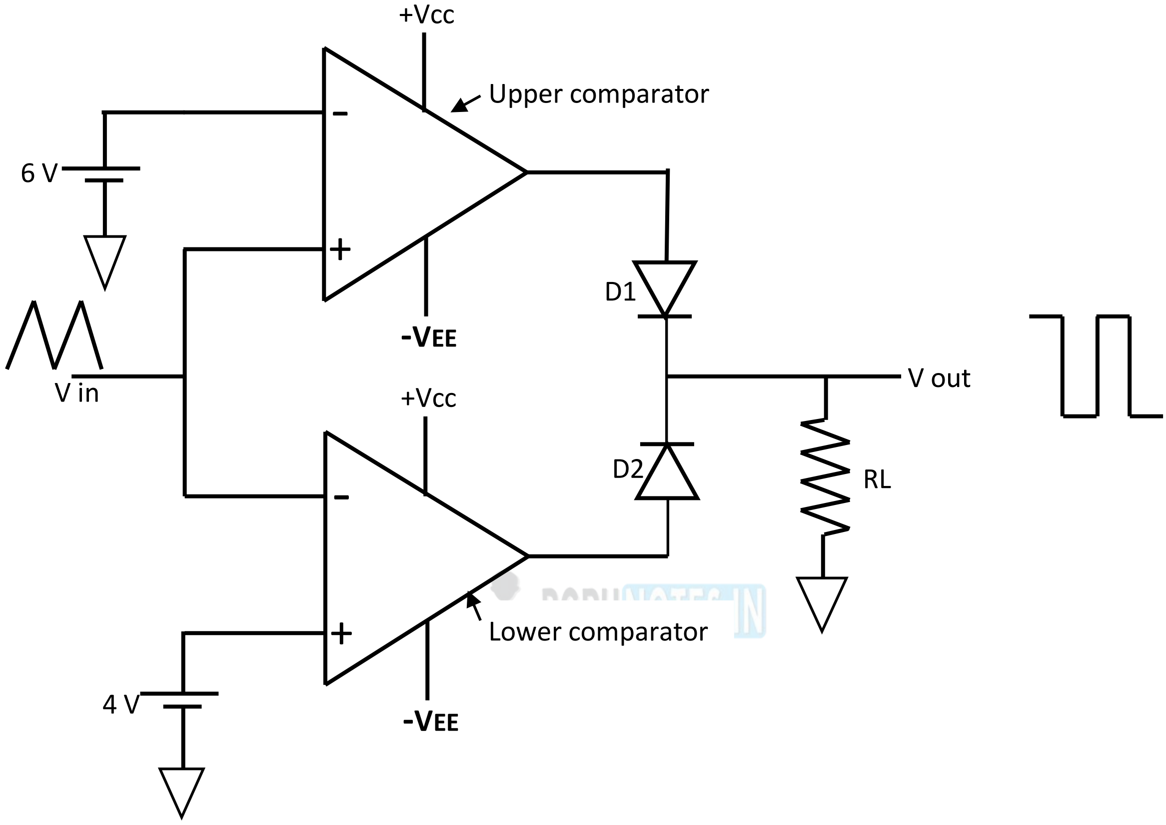


Figure 4 circuit of window comparator using operational amplifier

The working of window comparator is defined with the help of three cases. In the circuit diagram the comparators are set to 6V and 4V as a fixed input and a common input waveform is applied to upper and lower comparator. The input and output waveform of window comparator using operational amplifier is shown in figure 5.

Case 1: When the input signal is within the window:

Suppose 5 Volts:

Upper comparator:-V_{sat} Diode D1 reversed biased

Lower Comparator:-V_{sat} Diode D2 reversed biased

Output: Zero

Case 2: When the input signal is above 6 Volts:

Suppose 7 Volts:

Upper comparator:+V_{sat} Diode D1 forward biased

Lower Comparator:-V_{sat} Diode D2 reversed biased

Output: +V_{sat}

Case 3: When the input signal is below 4 Volts:

Suppose 3 Volts:

Upper comparator: -V_{sat} Diode D1 reversed biased

Lower Comparator: +V_{sat} Diode D2 forward biased

Output: + V_{sat}

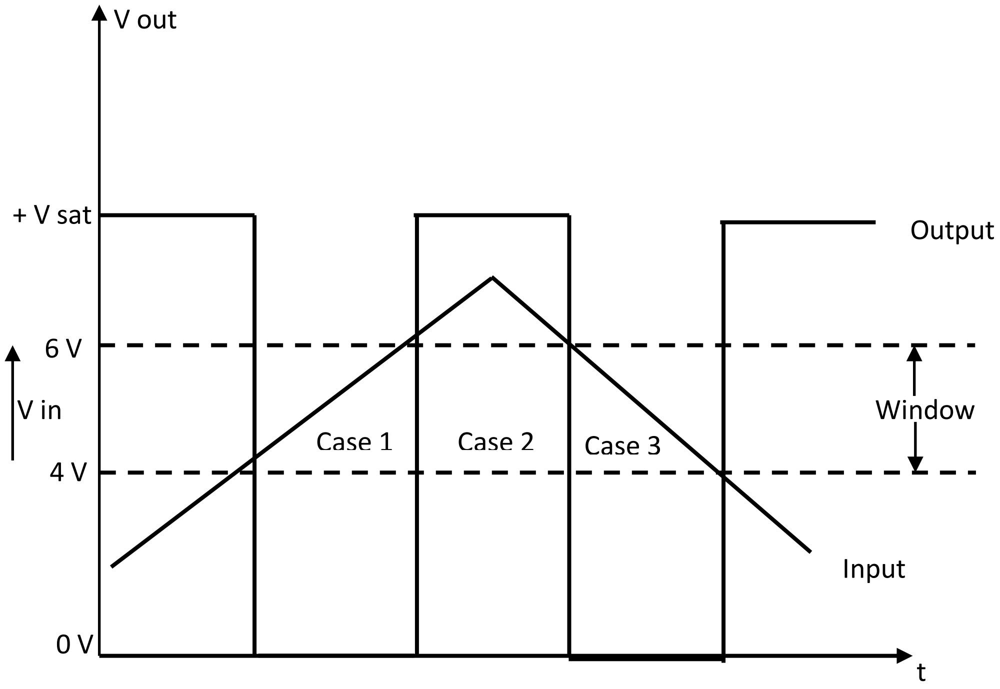


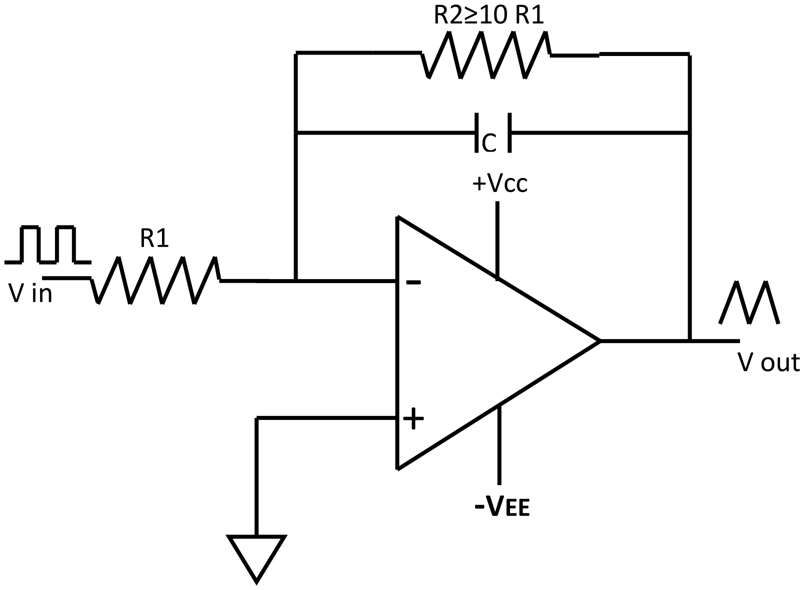
Figure 5 Input and output waveform of window comparator using operational amplifier

Op-amp as rectangular to triangular pulse converter

A rectangular wave is applied to the input of inverting terminal of the op amp through R1 as shown in figure 6 .During high pulse of the rectangular wave the ramp decreases as shown in figure 6 integrator output. Therefore the output is a triangular wave of the same frequency as that of the rectangular .The peak to peak output voltage is expressed by:

$$V_{out(pp)} = \frac{V_{in(pp)}}{4fR_1}$$

Because a capacitor appears open at zero frequency, the input offset may saturate the op amp (without R2). To avoid this, R2 which more than 10R1 is usually shunted across the capacitor. The shunt resistance R2 has virtually no effect on the output, provided the input frequency is much greater than $f = \frac{1}{2\pi R_2 C}$



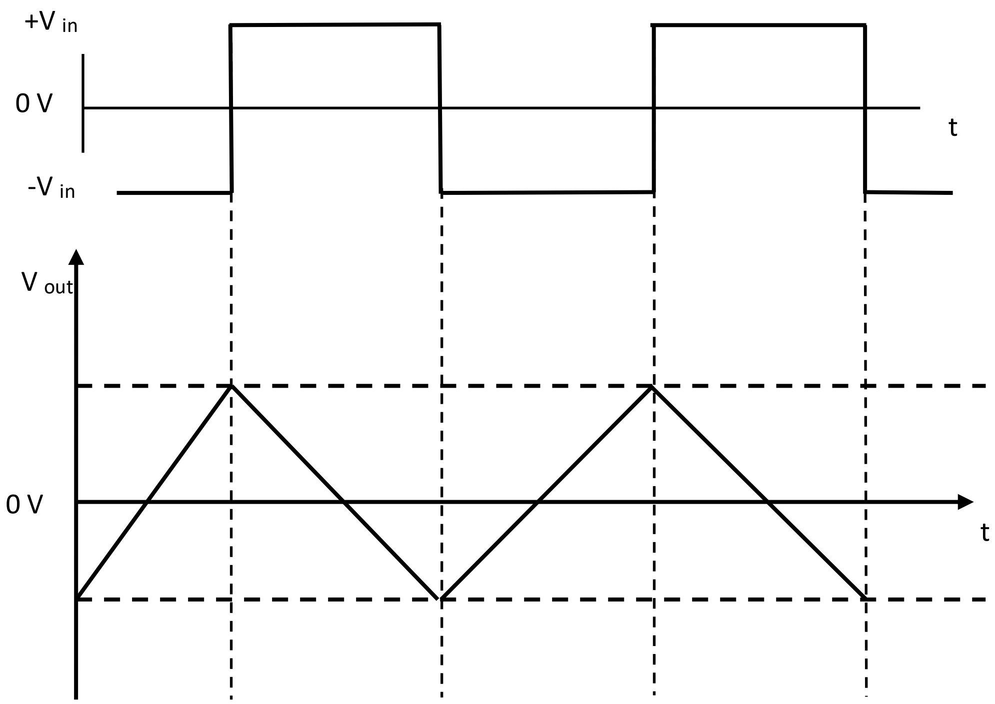


Figure 6 rectangular to triangular pulse converter circuit diagrams with related input and output waveform

Schmitt Trigger

A Schmitt trigger is basically an inverting comparator circuit with a positive feedback. The purpose of the Schmitt trigger is to convert any regular or irregular shaped sinusoidal input waveform into a square wave output pulse. The figure 7 shows the circuit diagram of Schmitt trigger circuit.

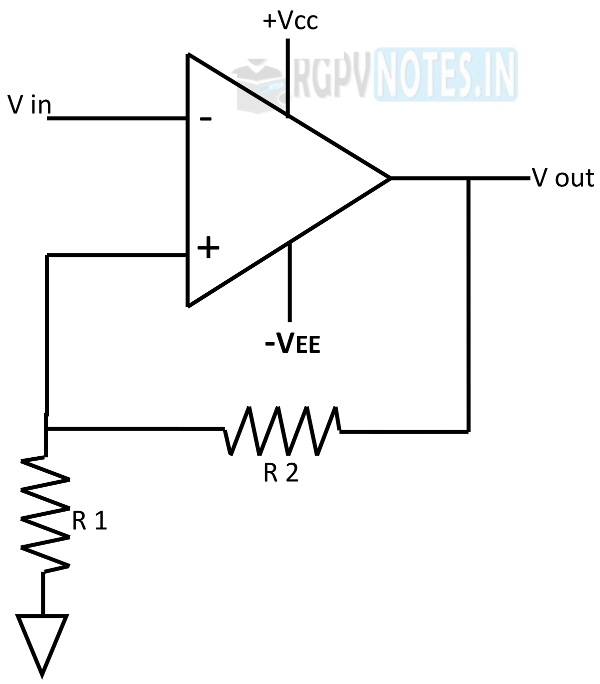


Figure 7 Circuit diagram of Schmitt trigger

As shown in figure7, a voltage divider with resistors R1 and R2 is set in the positive feedback of the op-amp. The voltage across R1 is feed back to the non-inverting input. The input voltage V_{in} triggers the state of output every time it exceeds its voltage levels above a certain threshold value called Upper Threshold Voltage (V_{ut}) and Lower Threshold Voltage (V_{lt}).

Let us assume that the inverting input voltage has a slight positive value. This will cause a negative value in the output. This negative voltage is feed back to the non-inverting terminal (+) of the op-amp through the voltage divider. Thus, the value of the negative voltage that is feed back to the positive terminal becomes higher. The value of the negative voltage becomes again higher until the circuit is driven into negative saturation ($-V_{sat}$). Now, assume that inverting input voltage has a slight negative value. This will cause a positive value in the output. This positive voltage is fed back to the non-inverting terminal (+) of the op-amp through the voltage divider. Thus, the value of the positive voltage that is fed back to the positive terminal becomes higher. The value of the positive voltage becomes again higher until the circuit is driven into positive saturation ($+V_{sat}$). The waveform Schmitt trigger is shown in figure 8.

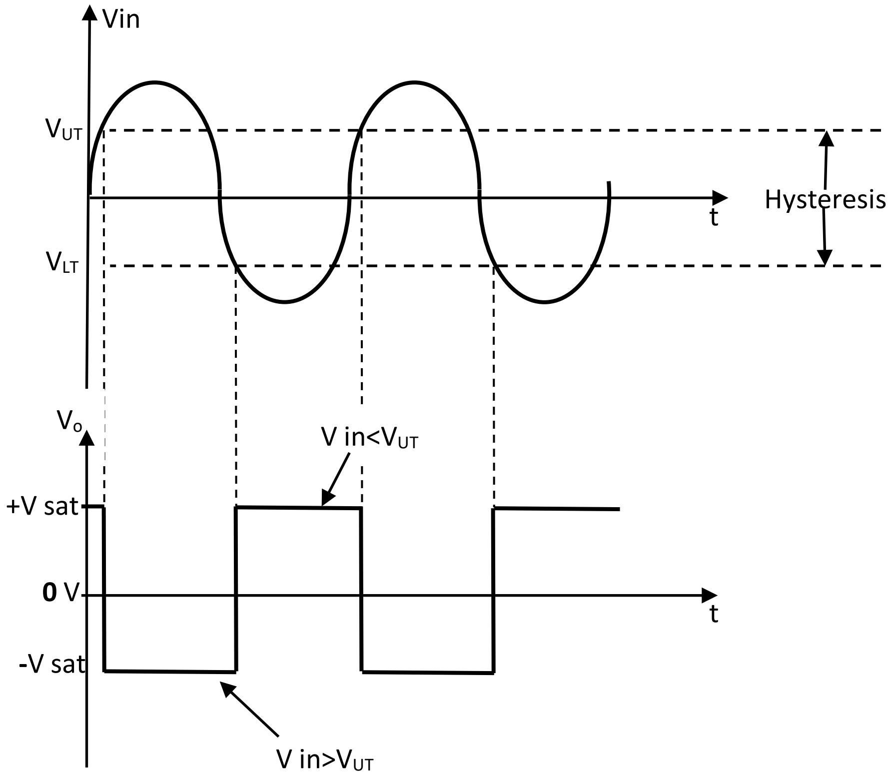


Figure 8 Schmitt trigger waveform

When V_{out} = $+V_{sat}$, the voltage across R_1 is called Upper Threshold Voltage (V_{ut}). The input voltage, V_{in} must be slightly more positive than V_{ut} in order to cause the output Vo to switch from $+V_{sat}$ to $-V_{sat}$. When the input voltage is less than V_{ut}, the output voltage V_{out} is at $+V_{sat}$.

Upper Threshold Voltage, $V_{ut} = +V_{sat}$ (R1/R1+R2)

When V_{out} = $-V_{sat}$, the voltage across R_1 is called Lower Threshold Voltage (V_{lt}). The input voltage, V_{in} must be slightly more negative than V_{lt} in order to cause the output Vo to switch from $-V_{sat}$ to $+V_{sat}$. When the input voltage is less than V_{lt}, the output voltage V_{out} is at $-V_{sat}$.

Lower Threshold Voltage, $V_{lt} = -V_{sat}$ (R1/R1+R2)

If the value of V_{ut} and V_{lt} are higher than the input noise voltage, the positive feedback will eliminate the false output transitions. With the help of positive feedback and its regenerative behavior, the output voltage will switch fast between the positive and negative saturation voltages.

Applications of Schmitt Trigger

Schmitt trigger is mostly used to convert a very slowly varying input voltage into an output having abruptly varying waveform occurring precisely at certain predetermined value of input voltage. Schmitt trigger may be used for all applications for which a general comparator is used. Any type of input voltage can be converted into its corresponding square signal wave. The only condition is that the input signal must have large enough excursion to carry the input voltage beyond the limits of the hysteresis range. The amplitude of the square wave is independent of the peak-to-peak value of the input waveform.

Op-amp as triangular to rectangular pulse converter

Figure 9 shows a variable reference voltage is maintained to the input of inverting terminal of the operational amplifier. The triangular wave is applied to the non-inverting input. If the triangular input is more than V_{ref}, the output will switch over to the positive saturation $+V_{sat}$ as shown in figure (b).By varying R2, the width of the output pulse and duty cycle $D = \frac{W}{T}$ can be changed.

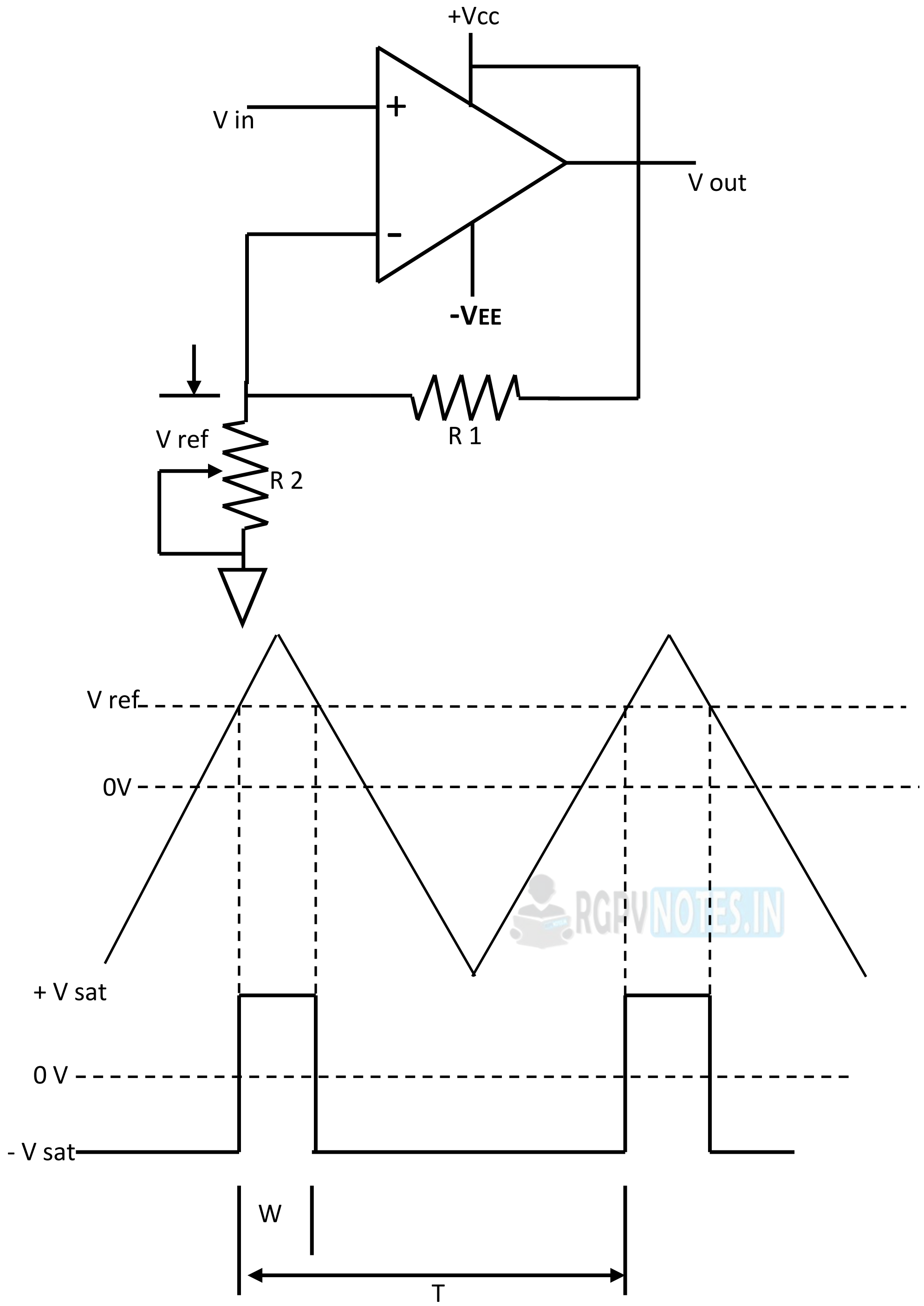


Figure 9 triangular to rectangular pulse converter circuit diagrams with related input and output waveform

Wien bridge oscillator

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 .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 $ƒ_r$ the phase shift is 0°. The figure 10 shows the two-stage RC coupled amplifier circuit.

The RC phase shift network consists of a series connected RC circuit to a parallel connected RC circuit forming basically a High Pass Filter connected to a Low Pass Filter producing a very selective second-order frequency dependant Band Pass Filter.

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 V_{in}. Therefore there is no output signal, V_{out}. 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*, (ƒr).

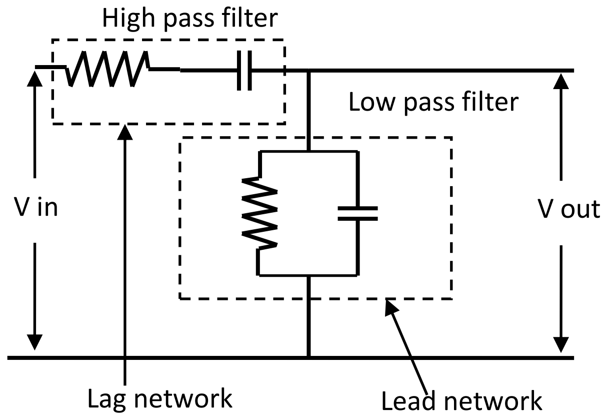


Figure 10 RC phase shift network

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 in figure 11.

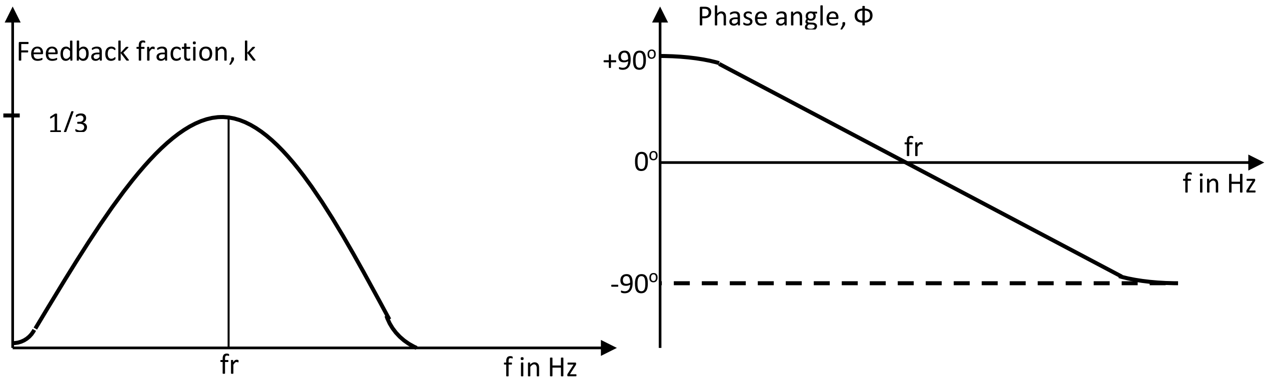


Figure 11 feedback fraction V/S Frequency and phase angle V/S frequency curve

From the figure it is clear 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, (ƒr) with the two signals being “in-phase” or 0°. We can therefore define this resonant frequency point with the following expression.

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

Where:
f_r is the Resonant Frequency in Hertz
R is the Resistance in Ohms
C is the Capacitance in Farads
Then this frequency selective RC network forms the Wien Bridge Oscillator circuit which is shown in figure 12. If we now place this RC network across a non-inverting amplifier which has a gain of $1 + \frac{R_1}{R_2}$ the following oscillator circuit is produced.
Working:
The feedback signal in this oscillator circuit is connected to the non-inverting input terminal so that the op-amp works as a non-inverting amplifier.
The condition of zero phase shifts around the circuit is achieved by balancing the bridge, zero phase shifts is essential for sustained oscillations.
The frequency of oscillation is the resonant frequency of the balanced bridge and is given by the expression

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

At resonant frequency (f_r), the inverting and non-inverting input voltages will be equal and “in-phase” so that the negative feedback signal will be cancelled out by the positive feedback causing the circuit to oscillate.
From the analysis of the circuit, it can be seen that the feedback factor 1/3 at the frequency of oscillation. Therefore for sustained oscillation, the amplifier must have a gain of 3 so that the loop gain becomes unity.
For an inverting amplifier the gain is set by the feedback resistor network R3and R4and is given as the ratio –R3/R4.

The required frequency of oscillation f_r is given by

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

Gain of the amplifier section is given by,

$$A = 1 + \frac{R_3}{R_4} = 1 + \frac{R_3}{\frac{R_3}{2}} = 1 + 2 = 3$$

Since lead-lag circuit has a k=$\frac{1}{3}$, the loop gain is $kA_v = \frac{1}{3} \times 3 = 1$

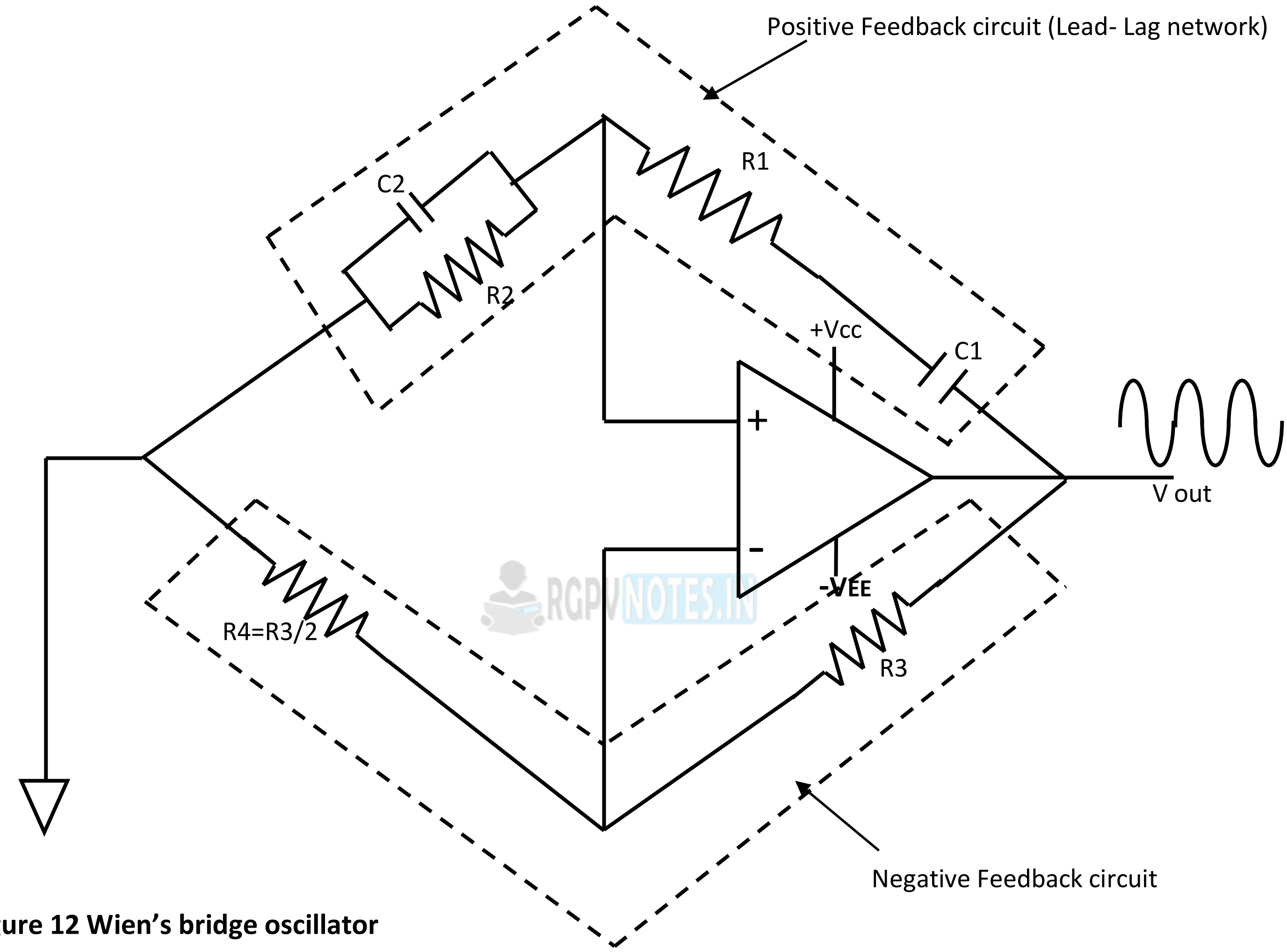


Figure 12 Wien's bridge oscillator

As the oscillations build up , the peak to peak output becomes large enough to increase the resistance of tungsten lamp .When its resistance is equals to $\frac{R_3}{2}$, the loop gain as 1.At this point the oscillation becomes stable, and the output voltage has a constant peak to peak value.

Function generator

Function generator is used for generation of various types of waveforms like sinusoidal, rectangular and triangular which can be generated with the help of cascaded Wien's bridge oscillator, Schmitt trigger and Integrator.

Wien's bridge oscillator: 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 .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°.

Schmitt trigger: A Schmitt trigger is basically an inverting comparator circuit with a positive feedback. The purpose of the Schmitt trigger is to convert any regular or irregular shaped sinusoidal input waveform into a square wave output pulse. Let us assume that the inverting input voltage has a slight positive value. This will cause a negative value in the output. This negative voltage is feed back to the non-inverting terminal (+) of the op-amp through the voltage divider. Thus, the value of the negative voltage that is feed back to the positive terminal becomes higher. The value of the negative voltage becomes again higher until the circuit is driven into negative saturation ($-V_{sat}$). Now, assume that inverting input voltage has a slight negative value. This will cause a positive value in the output. This positive voltage is fed back to the non-inverting terminal (+) of the op-amp through the voltage divider. Thus, the value of the positive voltage that is fed back to the positive terminal becomes higher. The value of the positive voltage becomes again higher until the circuit is driven into positive saturation ($+V_{sat}$).

Integrator: A rectangular wave is applied to the input of inverting terminal of the op amp through R1 as shown in figure 13 .During high pulse of the rectangular wave the ramp decreases as shown in figure 13 integrator output. Therefore the output is a triangular wave of the same frequency as that of the rectangular .The peak to peak output voltage is expressed by:

$$V_{out(pp)} = \frac{V_{in(pp)}}{4fR_1}$$

Because a capacitor appears open at zero frequency, the input offset may saturate the op amp (without R2). To avoid this, R2 which more than 10R1 is usually shunted across the capacitor. The shunt resistance R2 has virtually no effect on the output, provided the input frequency is much greater than $f = \frac{1}{2\pi R_2 C}$

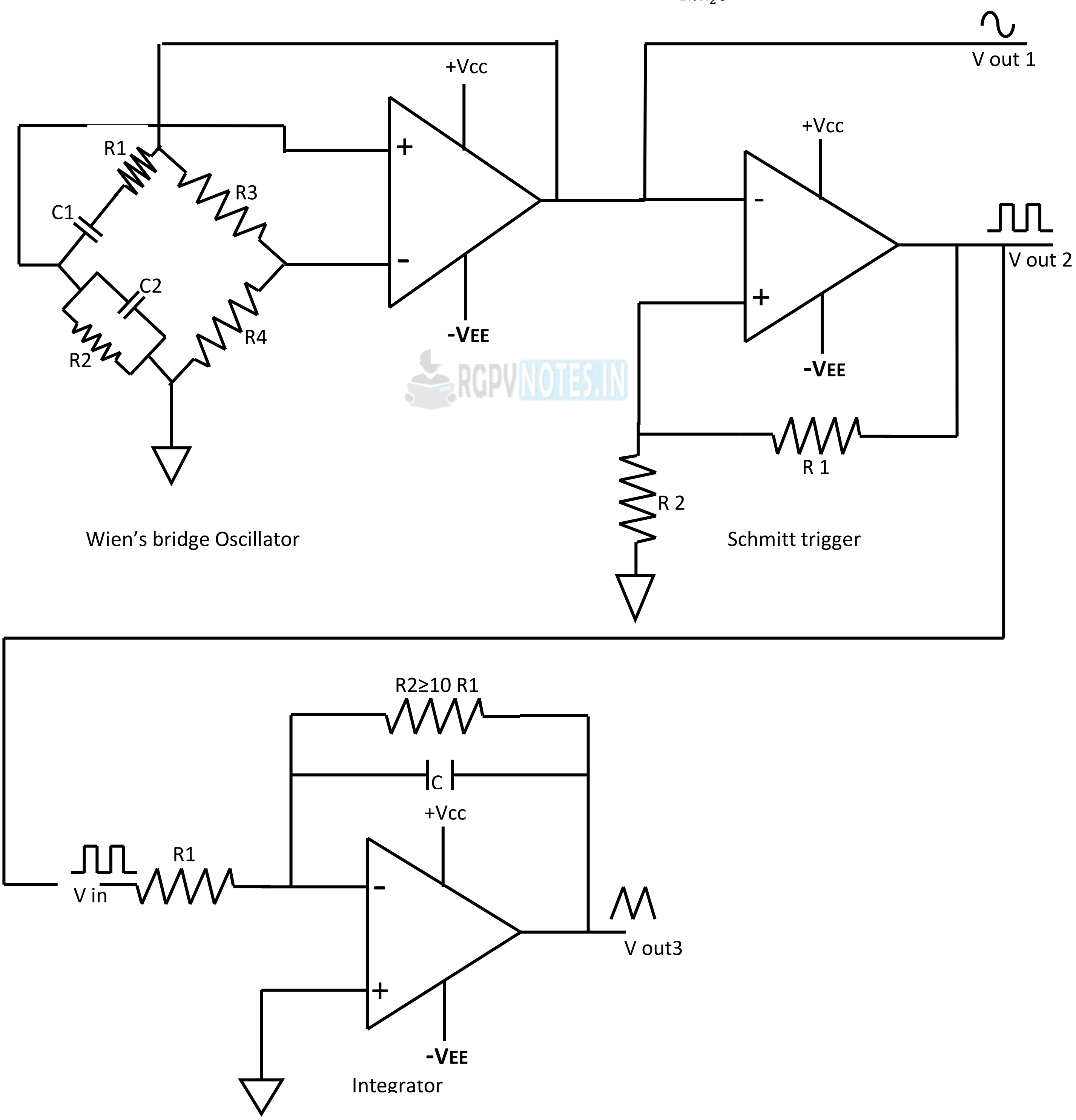


Figure 13 Circuit diagram of function generator

Frequency response of OP-AMP

Variations in the frequency will cause change in the gain magnitude and its phase angle. The manner in which the gain of the operational amplifier responds to different frequencies is called frequency response. A graph of the magnitude of the gain versus frequency is called the frequency response plot. Gain magnitude is expressed in dB and frequency on a logarithmic scale to accommodate a large frequency range. Op amp requires external compensating components are called uncompensated op amps.

In figure 14 shows the frequency at 100 Hz is called break frequency where gain is actually 3dB less than that at lower frequencies. For frequencies between f1 and f2 the gain decreases by-20dB for a decade of the frequency. This means that for a increase in frequency the voltage gain falls by 20dB.At frequency f2 the gain decreases by-40dB /decade and at f3 the gain decreases by -60dB/decade at the cross over frequency the system becomes unstable. It can break into oscillations and generate sine wave. The proper selection of compensating network makes the amplifier stable.

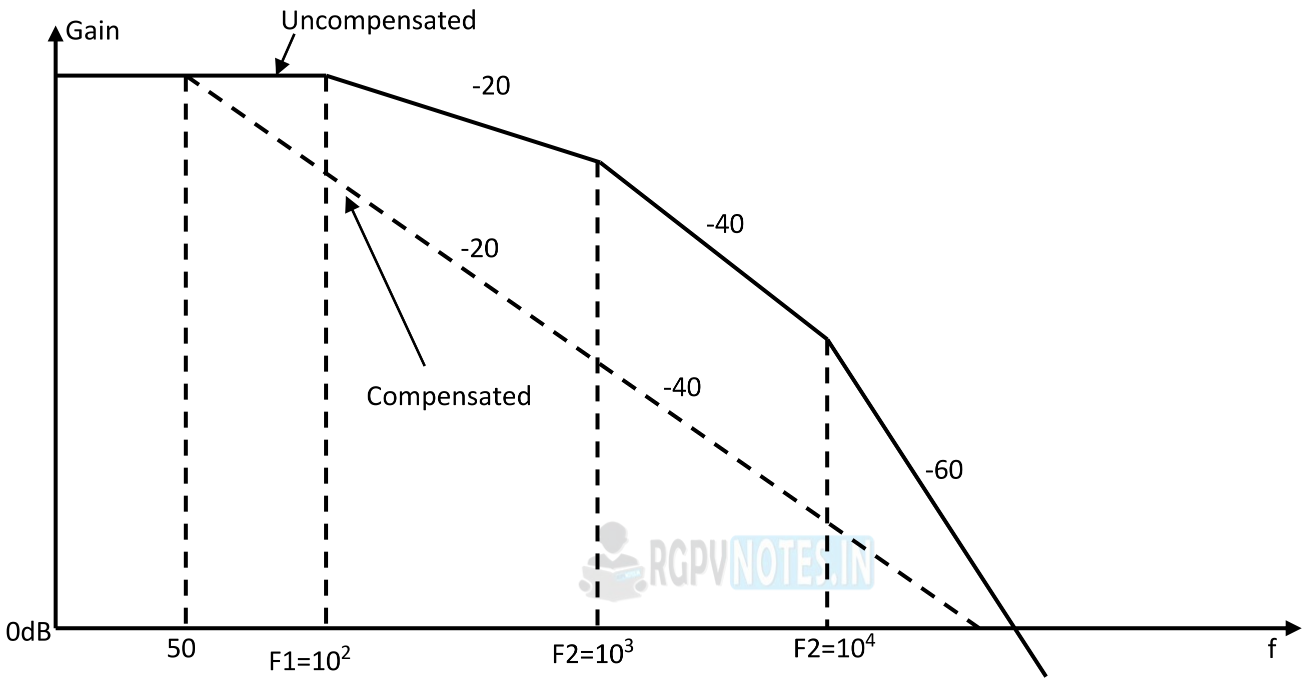


Figure 14 Frequency response of operational amplifier

Simplified circuit diagram of OP-AMP

Figure 15 shows the simplified circuit diagram of the 741 IC. It has following stages

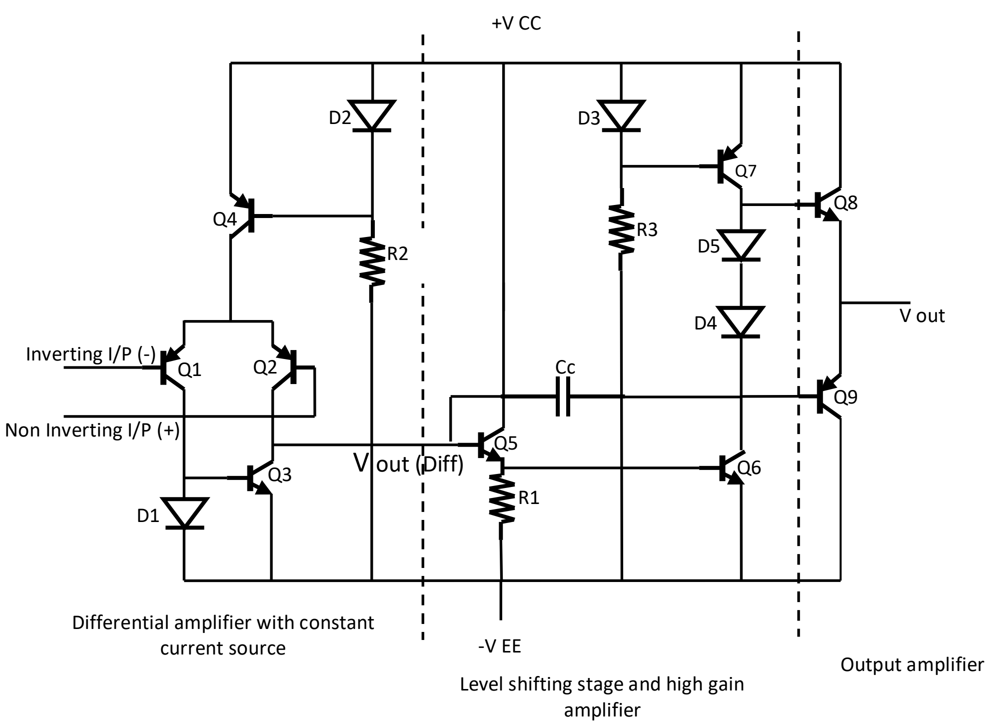


Figure 15 simplified circuit diagram of the 741 IC

1. Input stage:
   Input stage is the differential amplifier using PNP transistor Q1 and Q2. Transistor Q4 acts as constant current source and R2 and D2 control the bias on Q4 which maintains the tail current of the differential amplifier,Q3 acts an active load resistor that gives extremely high impedance and due to this the voltage gain is much higher.
2. Level shifting stage:
   The amplified signal from input stage drives the transistor Q5 which step up the input impedance. The level shifter circuit is used to shift the dc level at the output to zero volts w. r. t. ground when the two input terminals are grounded.
3. High gain amplifier
   The signal out of Q5 goes to Q6 which acts as driver for the output stage. Diode D4 and D5 are part of biasing for the output stage.Q7 behaves as an active load resistor for Q6. Q6 and Q7 are like a CE stage with very high voltage gain.
4. Output Stage:
   The final stage consists of Q8 and Q9 is a push-pull amplifier. The output stage increases the output voltage swing and raises the current supplying capability of the op-amp. Diode D4 and D5 compensate for changes in temperature caused by Q8 and Q9. A coupling capacitor is used to prevent amplifier from unwanted signals.

Power supplies for integrated circuits

Most linear integrated chips use one or more differential amplifier stages which require both a positive and negative power supply for proper operation of the circuit. When a single supply is used it is normally necessary to connect an extra circuit to the IC as shown in figure 16. Some of the dual supply op amp ICs can also be operated from a single supply voltage, provided that a special external circuit is used.

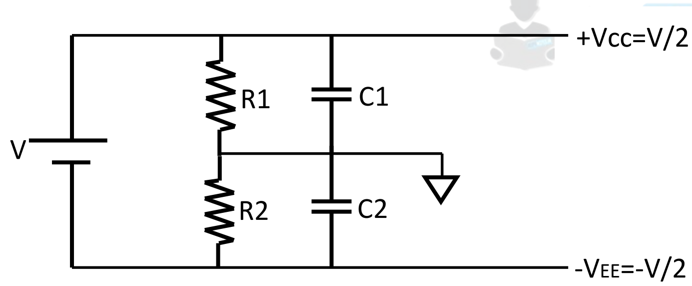


Figure 16 Power Supply for operational amplifiers

First order Low-pass filter using OP-AMP

The simplest form of first order active low pass filter consists of a passive RC filter stage providing a low frequency path to the input which is connected to a unity gain non-inverting amplifier. The function of low pass filter is to pass low frequency and pass higher frequency to ground using capacitor. First order active low pass filter circuit with unity feedback is as shown in figure 17.

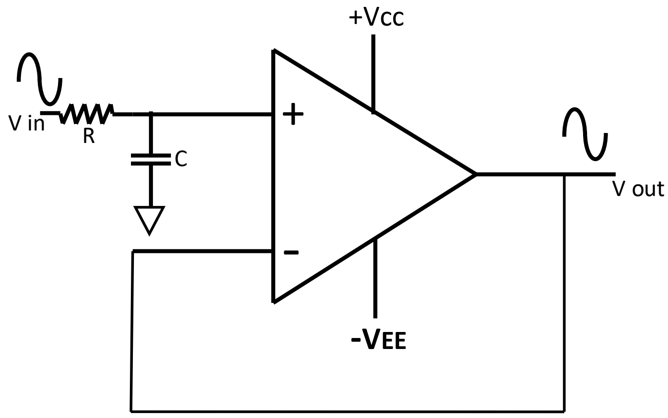


Figure 17 First order active low pass filter circuit with unity feedback

Advantage

1. The operational amplifier have high input impedance which prevents excessive loading on the filters output while its low output impedance prevents the filters cut-off frequency point from being affected by changes in the impedance of the load.
2. Provides good stability to the filter,

Disadvantage

1. No voltage gain above one.

Active Low Pass Filter with Amplification

Active Low Pass Filter with Amplification can be achieved using the circuit diagram as shown in figure 18. The amplification can be achieved with the help of non inverting amplifier with feedback.

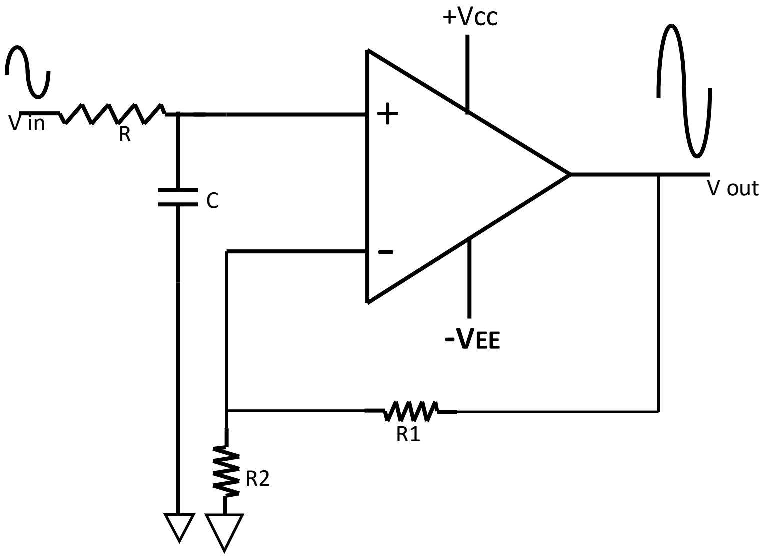


Figure 18 Active low Pass Filter with Amplification

For a non-inverting amplifier, the magnitude of the voltage gain for the filter is given as a function of the feedback resistor (R1) divided by its corresponding input resistor (R2) value and is expressed by:

$$DC\ gain = \left(1 + \frac{R_1}{R_2}\right)$$

Therefore, the gain of an active low pass filter as a function of frequency will be:

Gain of a first-order low pass filter

$$\boldsymbol{Voltage\ gain A_v = \frac{V_{out}}{V_{in}} = \frac{A_f}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}}}$$

Where:

A_f = pass band gain of the filter, (1 + R2/R1)

f = frequency of the input signal in Hertz, (Hz)

f_c = cut-off frequency in Hertz, (Hz)

Thus, the operation of a low pass active filter can be verified from the frequency gain equation above as:

1. At very low frequencies, $f < f_c \ \frac{V_{out}}{V_{in}} = A_f$
2. At the cut-off frequency, $f = f_c \ \frac{V_{out}}{V_{in}} = \frac{A_f}{\sqrt{2}} = 0.707A_f$
3. At very high frequencies, $f > f_c \ \frac{V_{out}}{V_{in}} < A_f$

Active Low Pass Filter has a constant gain A_f from 0 Hz to the high frequency cut-off point, f_c . At f_c the gain is$0.707A_f$, and after f_c it decreases at a constant rate as the frequency increases. That is, when the frequency is increased one decade, the voltage gain is divided by 10.

In other words, the gain decreases 20dB (= 20log 10) each time the frequency is increased by 10. When dealing with filter circuits the magnitude of the pass band gain of the circuit is generally expressed in *decibels* or *dB* as a function of the voltage gain and this is expressed as:

Magnitude of Voltage Gain in (dB)

$$\boldsymbol{A_v(dB) = 20log_{10}\frac{V_{out}}{V_{in}}}$$

$$-3dB = 20log_{10}0.707\frac{V_{out}}{V_{in}}$$

The cut-off or corner frequency (f_c) is given

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

Second order Low-pass filter using OP-AMP

A first-order low-pass active filter can be converted into a second-order low pass filter by simply adding one additional RC network in the input path. The frequency response of the second-order low pass filter is identical to that of the first-order, except that the stop band roll-off will be twice the first-order filter at 40dB/decade (12dB/octave). The figure 19 shows the circuit diagram of Second order Low-pass filter using OP-AMP and related frequency response.

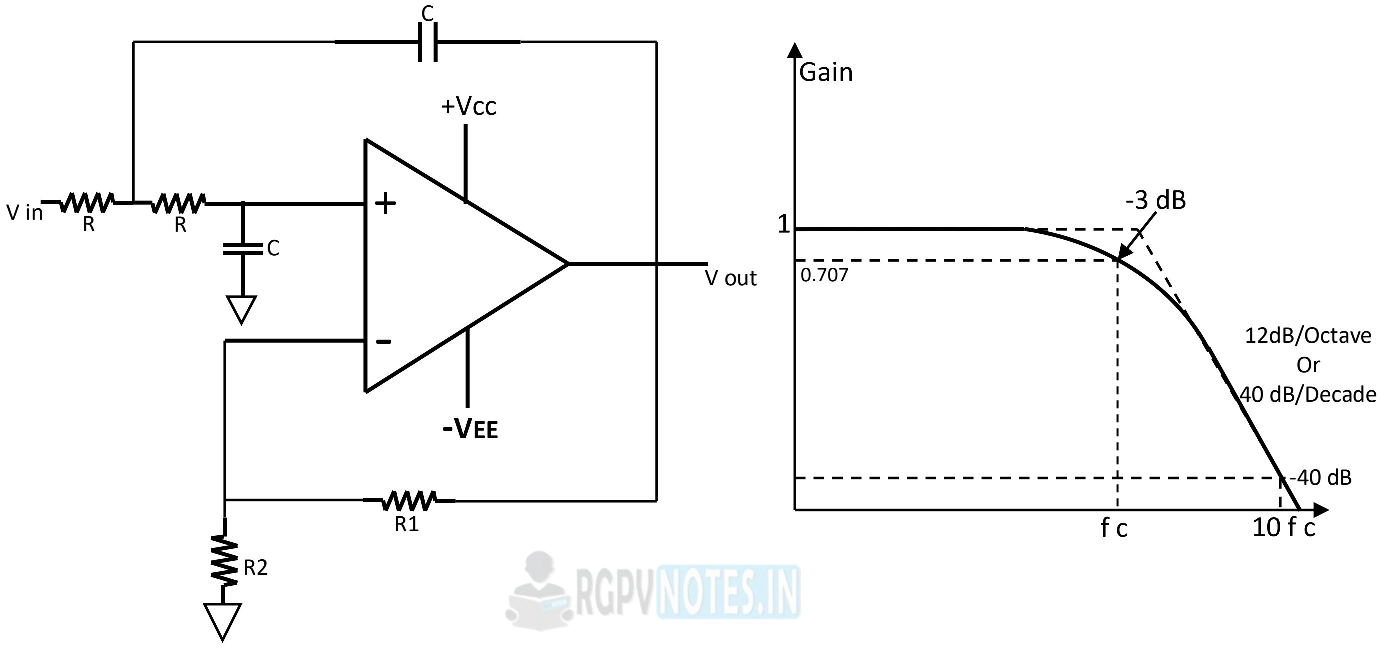


Figure 19 second order Low-pass filter using OP-AMP and related frequency response

When cascading together two low pass filter circuits to form higher-order filters, the overall gain of the filter is equal to the product of each stage.

First order high-pass filter using OP-AMP

The simplest form of first order active high pass filter consists of a passive RC filter stage providing a high frequency path to the input by using capacitor in series with input signal and is connected to a unity gain non-inverting amplifier. The function of high pass filter is to pass high frequency and pass low frequency to ground using capacitor. First order active high pass filter circuit with unity feedback is as shown in figure 20.

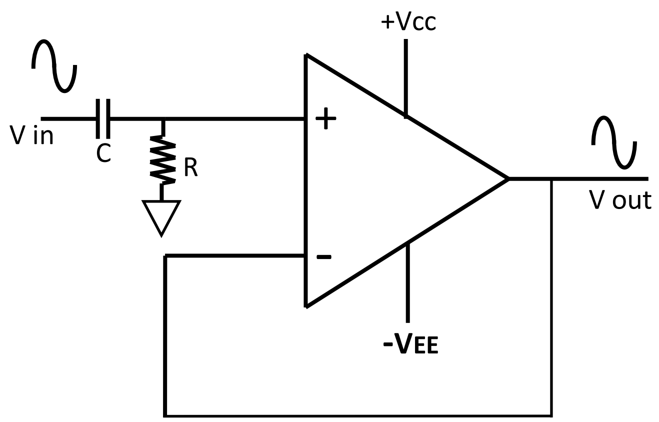


Figure 20 First order active high pass filter circuit with unity feedback

Active high Pass Filter with Amplification

Active high Pass Filter with Amplification can be achieved using the circuit diagram as shown in figure21. The amplification can be achieved with the help of non inverting amplifier with feedback.

For a non-inverting amplifier, the magnitude of the voltage gain for the filter is given as a function of the feedback resistor (R1) divided by its corresponding input resistor (R2) value and is expressed by:

$$DC\ gain = \left(1 + \frac{R_1}{R_2}\right)$$

Therefore, the gain of an active high pass filter as a function of frequency will be:

$$\boldsymbol{Voltage\ gain A_v} = \frac{\boldsymbol{V_{out}}}{\boldsymbol{V_{in}}} = \frac{\boldsymbol{A_f\left(\frac{f}{f_c}\right)}}{\sqrt{\boldsymbol{1 + \left(\frac{f}{f_c}\right)^2}}}$$

Where:
$\boldsymbol{A_f}$ = pass band gain of the filter, (1 + R2/R1)
$\boldsymbol{f}$ = frequency of the input signal in Hertz, (Hz)
$\boldsymbol{f_c}$ = cut-off frequency in Hertz, (Hz)

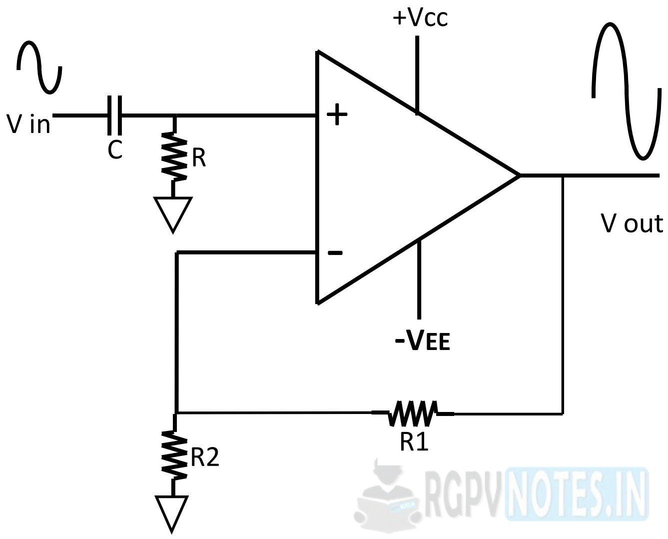


Figure 21 Active high Pass Filter with Amplification

Thus, the operation of a high pass active filter can be verified from the frequency gain equation above as:

1. At very low frequencies, $\boldsymbol{f < f_c \frac{V_{out}}{V_{in}} < A_f}$
2. At the cut-off frequency, $\boldsymbol{f = f_c \frac{V_{out}}{V_{in}} = \frac{A_f}{\sqrt{2}} = 0.707A_f}$
3. At very high frequencies, $\boldsymbol{f > f_c \frac{V_{out}}{V_{in}} = A_f}$

Active high Pass Filter has a constant gain A_f that increase from 0 Hz to the low frequency cut-off point, f_c. At f_c the gain is $0.707A_f$, and after f_c all frequencies are passed so the filter has a constant gain A_F with the highest frequency being determined by the closed loop bandwidth of the op-amp.

When dealing with filter circuits the magnitude of the pass band gain of the circuit is generally expressed in *decibels* or *dB* as a function of the voltage gain and this is expressed as:

Magnitude of Voltage Gain in (dB)

$$\boldsymbol{A_v(dB) = 20log_{10}\frac{V_{out}}{V_{in}}}$$

$$\textbf{-3dB=}\ \boldsymbol{20log_{10}0.707\frac{V_{out}}{V_{in}}}$$

For a first-order filter the frequency response curve of the filter increases by 20dB/decade or 6dB/octave up to the determined cut-off frequency point which is always at -3dB below the maximum gain value.

The cut-off or corner frequency ($\boldsymbol{f_c}$) is given

$$\boldsymbol{f_c = \frac{1}{2\pi RC}}$$

Second order High pass filters using OP-AMP

A first-order high-pass active filter can be converted into a second-order high pass filter by simply adding one additional RC network in the input path. The frequency response of the second-order high pass filter is identical to that of the first-order, except that the stop band roll-off will be twice the first-order filter at 40dB/decade (6 dB/octave). The figure 22 shows the circuit diagram of Second order high-pass filter using OP-AMP and related frequency response.

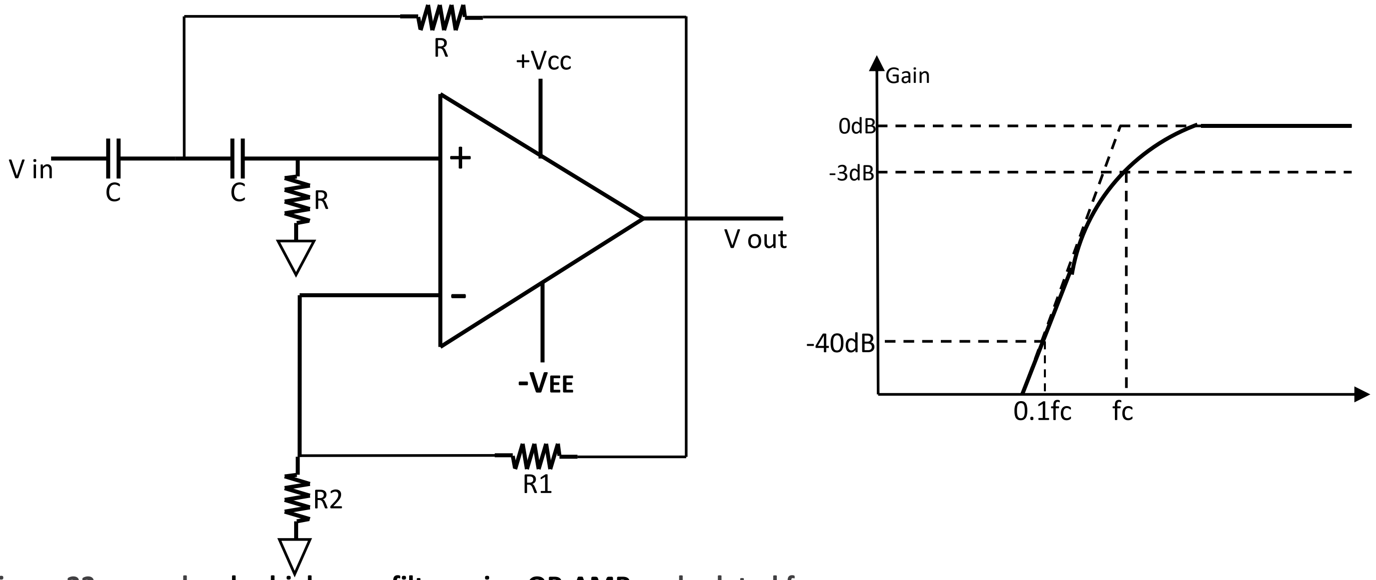


Figure 22 second order high-pass filter using OP-AMP and related frequency response

When cascading together two high pass filter circuits to form higher-order filters, the overall gain of the filter is equal to the product of each stage.

