Module 4 epc 1 - Operational amplifiers

Electronic principles and circuits (Visvesvaraya Technological University)

Module - 4

Negative feedback

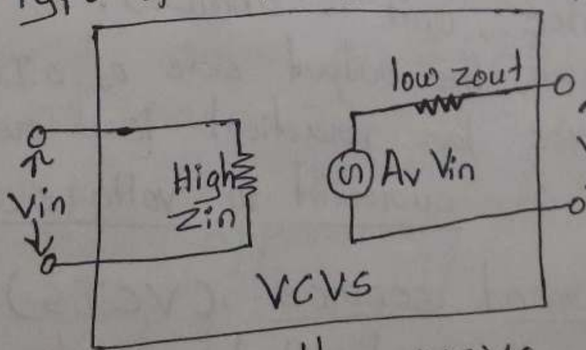
→ stabilizes the voltage gain.
→ Increases input impedance.
→ Decreases output ".

Four Types of Negative feedback.

1. Voltage - Controlled voltage source (VCVS)
2. Current - " " " (ICVS)
3. Voltage - " Current source (VCIS)
4. Current - " " " (ICIS)

1. Voltage controlled voltage source (VCVS)

→ The circuit with negative feedback that accepts voltage input & produces voltage output, is called voltage controlled voltage source.
→ Type of voltage amplifier.



→ Fig shows the VCVS, a voltage amplifier.
→ It is an ideal voltage amplifier because it has ideal characteristic like stabilized voltage gain, infinite input impedance & zero output impedance
→ Practical circuit has high - Zin, Low - Zout.
→ Av is the voltage gain.
→ As Zout approaches zero, output side of a VCVS is a stiff voltage source to any Practical load resistance.

2. Current controlled voltage source (ICVS)

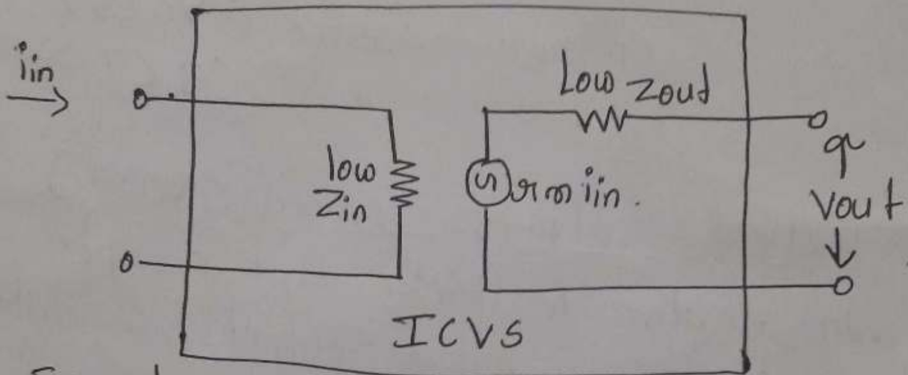
→ Type of the -ve feedback circuit that accepts current as a input & gives voltage as a output is called current controlled voltage source.

→ Input current controls an output voltage.

→ Also called as transient amplifier.

→ Because in V_{out}/I_{in} has unit ohms. & trans means taking ratio of an output quantity to an input quantity.

→ Type of transresistance amplifier.



→ Fig shows ICVS.

→ It has $Z_{in} = low$ $Z_{out} = low$.

→ r_m is the transresistance, unit is ohm(Ω).

→ As Zout approaches zero, the output side of a ICVS is a stiff voltage source for practical load resistances.

→ This circuit is also called as current to voltage converter

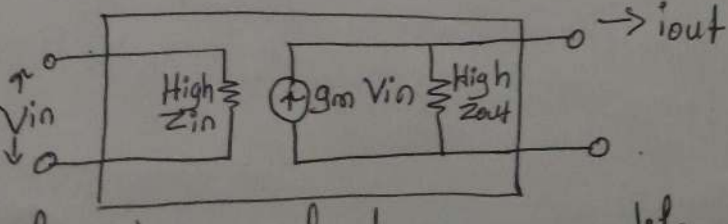
3. Voltage-controlled current source (VCIS)

→ Type of the -ve feedback circuit that accepts voltage as a input & gives current as an output is called voltage controlled current source.

→ It is also called as voltage to current converter

→ " " " " " trans conductance amplifier.

→ So, trans → ratio, conductance → (i_{out}/v_{in}) mhos or Siemens.

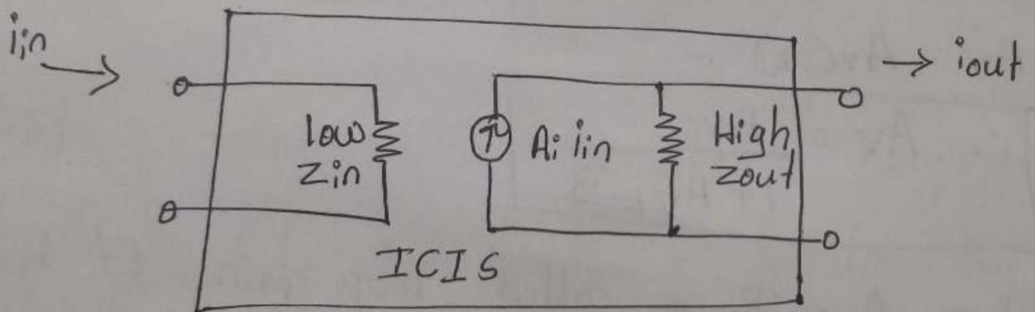


→ Type of transconductance amplifier.

→ Fig shows a VCIS.
→ It has Zin = high , Zout = high
→ gm represents transconductance.
→ As Zout approaches infinity, the output side of a VCIS is a stiff current source for load circuit.

4. Current-Controlled current source (ICIS)

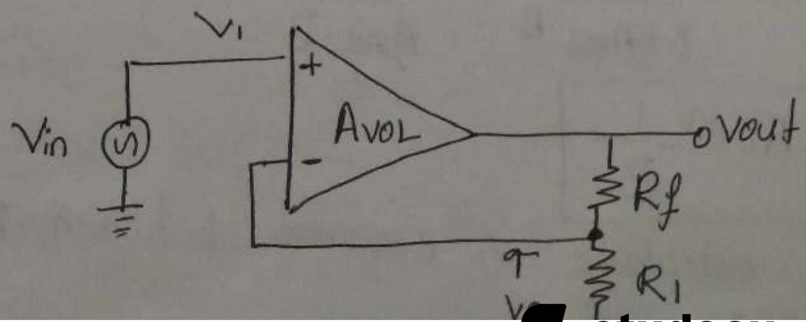
→ The type of a negative feedback that accepts current as a input & gives current as a output is called current-controlled current source.
→ It is a type of current amplifier.
→ It is a ideal current amplifier with stabilized current gain, zero input impedance & infinite output impedance.



→ Fig shows an ICIS.
→ It has Zin = low , Zout = high.
→ Ai is the current gain.
→ Zout approaches infinity, the output side of a VCVS is a stiff current source to any Practical load resistance.

VCVS voltage gain

→ non inverting amplifier circuit act as VCVS, therefore consider this to derive voltage gain.



Exact closed loop voltage gain

→ A_{VOL} is the open loop voltage gain of the amplifier.

→ V_{out} is feed back to the non-inverting input using voltage divider network called feed back network. It has a feedback gain or feedback fraction B.

$$\therefore B = \frac{\text{output}}{\text{input}} = \frac{V_2}{V_{out}}.$$

→ B is also called as feedback attenuation factor.

→ Closed loop voltage gain is given by,

$$A_{V(CL)} = \frac{A_{VOL}}{1 + A_{VOL} B}$$

$$A_V = A_{V(CL)}.$$

$$\boxed{\therefore A_V = \frac{A_{VOL}}{1 + A_{VOL} \cdot B}}$$

Loop gain - $A_{VOL} \cdot B$ is called loop gain. It is the voltage gain of the forward and feedback paths.

→ Larger loop gain stabilizes the loop gain and produces enhanced (better) gain stability, distortion, offsets, input impedance & output impedance.

Ideal closed loop voltage gain.

→ For the better performance of the VCVS it is good to keep loop gain >> 1 i,e $A_{VOL} \cdot B >> 1$

$$\therefore A_V = \frac{A_{VOL}}{1 + A_{VOL} \cdot B} \cong \frac{\cancel{A_{VOL}}}{\cancel{A_{VOL}} \cdot B}.$$

$$\boxed{A_V \cong \frac{1}{B}}$$

→ Formula to calculate % error between ideal & exact voltage gain.

$$\boxed{\%\ \text{error} = \frac{100\%}{1 + A_{VOL} \cdot B}}$$

Using Ideal Equation - we can derive B & Av interms of resistance.

→ according to voltage divider rule.

$$V_2 = \frac{R_1}{R_f + R_1} \cdot V_{out}$$

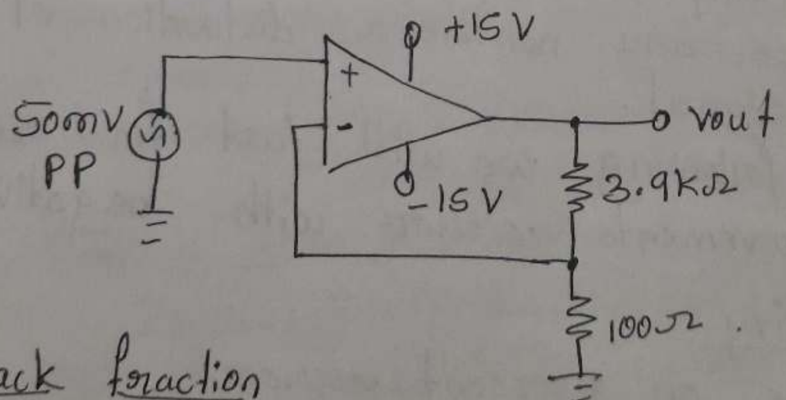
$$\frac{V_2}{V_{out}} = \boxed{B = \frac{R_1}{R_f + R_1}}$$

$$A_V \cong \frac{1}{B} \qquad \therefore A_V = \frac{R_1 + R_f}{R_1}$$

$$\boxed{A_V = \frac{R_f}{R_1} + 1}$$

which is same as voltage gain of non-inverting amplifier..

Example - Calculate the feedback fraction, the ideal closed loop voltage gain, the percent error and the exact closed-loop voltage gain. Use a typical A_{VOL} of 100,000 for the 741C.



feedback fraction

$$B = \frac{R_1}{R_1 + R_f} = \frac{100\Omega}{100\Omega + 3.9k\Omega} = 0.025$$

Ideal closed loop gain

$$A_V = \frac{1}{B} = \frac{1}{0.025} = 40.$$

the % error

$$\% \text{ error} = \frac{100\%}{1 + A_{VOL} B} = \frac{100\%}{1 + (100,000)(0.025} = 0.0$$

exact closed loop gain (A_V)

$$A_V = A_V - \underset{(\% \text{error})}{0.04\%} \cdot A_V$$

$$= 40 - (0.04\%) \, 40$$

$$A_V = 39.984$$

OR

$$A_V = \frac{A_{VOL}}{1 + A_{VOL} B} = \frac{100,000}{1 + (100,000)(0.025)} = 39.984$$

Practice - change the feedback resistor from 3.9kΩ to 4.9kΩ calculate the feedback fraction, the ideal-closed loop voltage gain, the % error & the exact closed loop gain.

Other VCVS Equations

→ Negative feedback in a VCVS amplifier increases the input impedance, decreases the output impedance and reduce any nonlinear distortion of the amplified signal.

→ ~~We~~ with following we will just find out how much improvements occurs with negative feedback.

Gain stability

→ It depends on percent error

→ The smaller the percent error, the better the stability.

→ The worst-case error of closed loop voltage gain occurs when the open-loop voltage gain is minimum.

$$\% \text{ Maximum error} = \frac{100\%}{1 + A_{VOL(min)} B}$$

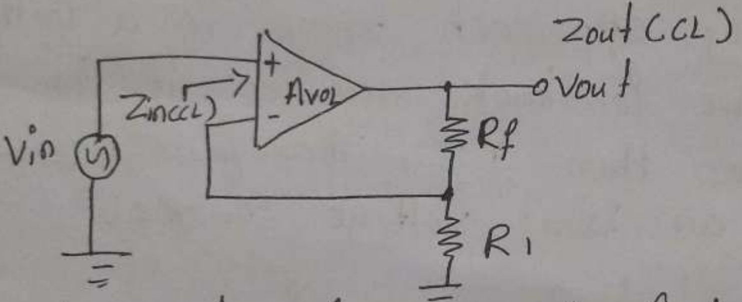
According to data sheet of 741 IC

$A_{VOL(min)} = 20,000$.

$\therefore \% \text{ maximum error} = \frac{100\%}{500} = 0.2\%$

→ In mass production the closed-loop voltage gain of any VCVS amplifier is within 0.2% of ideal value.

<u>Closed-Loop input impedance</u>.



→ Exact equation for the closed-loop input impedance of the VCVS amplifier.

$$Z_{in(CL)} = (1 + A_{VOL} B) R_{in} \| R_{cm}.$$

R_{in} = the open loop input resistance of the op-amp.

R_{cm} = the common-mode input resistance of the op-amp.

From the data sheet $R_{in} = 2M\Omega$.

" " " " $R_{cm} = R_E = 100 M\Omega$

→ often R_{cm} is ignored because it is large.

$\therefore Z_{in(CL)} \cong (1 + A_{VOL} B) R_{in}$.

→ In practical VCVS amplifier $(1 + A_{VOL} \cdot B) \gg 1$.

$Z_{in(CL)}$ will be extremely high.

→

→ ultimate limit on $Z_{in(CL)}$ is

$Z_{in(CL)} = R_{cm}$.

→ $Z_{in(CL)}$ is larger than R_{in} but less than ultimate limit on R_{cm}.

Closed-loop output impedance

→ Overall output impedance looking back into the VCVS amplifier is called closed loop output impedance. (Zout(CL))

→ Equation for $\boxed{Z_{out(CL)} = \dfrac{R_{out}}{1+A_{VOL}B}}$

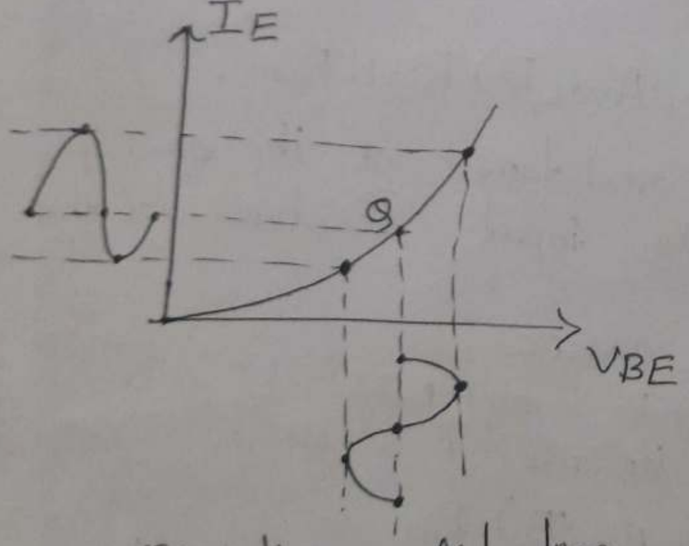
→ Rout → Open-loop output resistance of the opamp (as per data sheet of 741C Rout = 75Ω)

→ As (1+Avol·B) >> 1 in practical VCVS amplifier Zout(CL) is less than 1Ω.

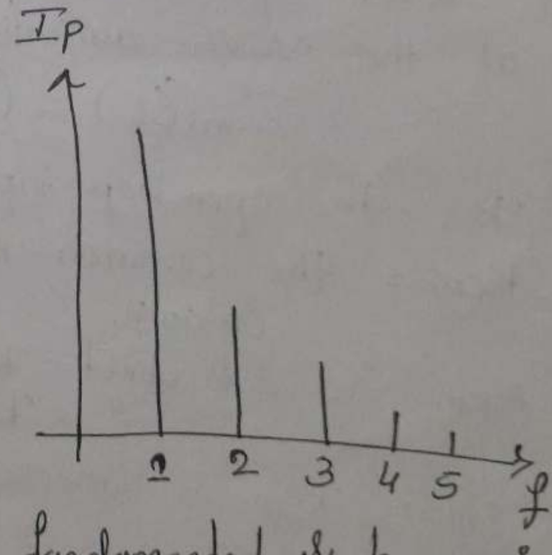
→ Zout (CL) may approach zero in a voltage fol

→ VCVS negative feedback reduces it to values much smaller then 1Ω. Therefore Zout(CL) approaches an ideal voltage source.

Non linear Distortion



non-linear distortion



fundamental & harmonics

→ In fig non linear graph of the base-emitter diode distorts a large signal by elongating the positive half cycle & compressing the -ve half cycle.

→ If 1kHz is the fundamental frequency rest 2,3,4,5 kHz are the harmonics.

→ RMS values of all the harmonics measured together

→ ∴ Nonlinear distortion is called as harmonic distortion.

→ Harmonic distortion can be measured by the instrument called a distortion analyzer.

→ Total Harmonic Distortion (THD) is given by the formula

$$THD = \frac{\text{Total harmonic voltage}}{\text{Fundamental voltage}} \times 100\%$$

Ex- If THV = 0.1 V rms & FV = 1V then THD = 10%

→ Negative feedback reduces harmonic distortion. equation for closed loop harmonic distortion is

$$\boxed{THD_{(CL)} = \frac{THD_{OL}}{1 + A_{VOL} B}}$$

where THD_{OL} → open loop harmonic distortion

THD_{CL} → closed-loop " "

→ As $1 + A_{VOL} B \gg 1$, so it reduces the harmonic distortion to negligible level.

→ In stereo amplifiers, we hear high-fidelity (HF) music instead of distorted sounds.

Discrete Negative feedback amplifier.

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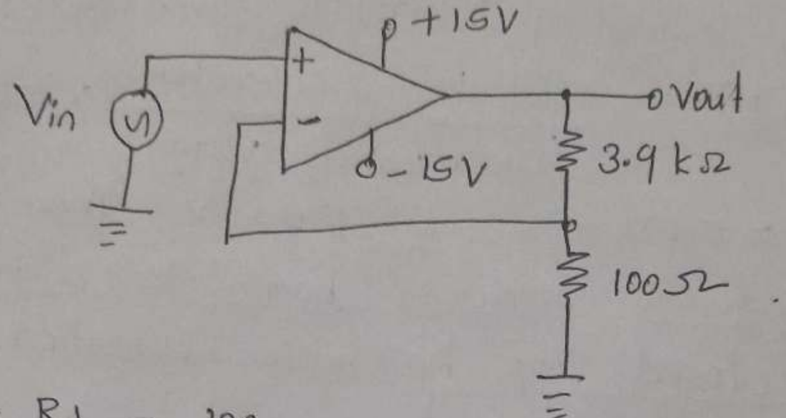
Example - In fig the 741C has an R_{in} of $2M\Omega$ & R_{cm} of $200 M\Omega$. what is the closed-loop input impedance? use $A_{VOL} = 1,00,000$ for 741C.



$$B = \frac{R_1}{R_1+R_f} = \frac{100}{100+3.9k} = 0.025.$$

$$\therefore 1 + A_{VOL} B = 1 + 1,00,000 \times 0.025 \cong 2500$$

$$Z_{in(CL)} \cong (1 + A_{VOL} B) \cdot R_{in} = 2500 \times 2 \times 10^6$$

$$\boxed{Z_{in(CL)} \cong 5000 M\Omega}$$

When $Z_{in(CL)} >> 100 M\Omega$ use the formula

$$Z_{in(CL)} = (\overset{5000 M\Omega}{\cancel{1 + A_{VOL} B}}) \parallel R_{CM}.$$

$$= (5000 M\Omega \parallel 200 M\Omega).$$

$$Z_{in(CL)} = 192 M\Omega$$

high $Z_{in(CL)}$ represents that VCVS approaches an ideal voltage amplifier.

* In fig change the 3.9 kΩ resistor to 4.9 kΩ & solve for $Z_{in(CL)}$

Example - with values $A_{VOL} = 1,00,000$, $R_f = 3.9k$ $R_1 = 100\Omega$ $R_{out} = 75\Omega$ calculate the closed loop output impedance

$$B = \frac{R_1}{R_1+R_f} = \frac{100}{100+3.9k} \cong \cancel{2500}\ 0.025.$$

$$1 + A_{VOL} \cdot B = 1 + 100,000 \cdot 0.025 \cong 2500.$$

$$Z_{out(CL)} = \frac{R_{out}}{(1 + A_{VOL} \cdot B)} = \frac{75}{2500} = 0.03\Omega$$

Low output impedance means that a VCVS aproaches an ideal voltage amplifier.

(15)

nple - Suppose the amplifier has an open-loop total harmonic distortion of 7.5 percent. What is the closed loop total harmonic distortion?

$$THD_{CL} = \frac{THD_{OL}}{1+A_{VOL}B} = \frac{7.5\%}{2500} = 0.003\%$$

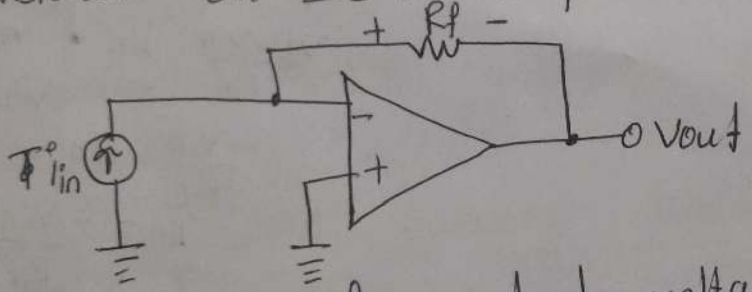
* repeat the same problem with 3.9kΩ resistor changed to 4.9kΩ.

* The ICVS amplifier.

→ It is an almost perfect current-to-voltage converter because it has zero input impedance & zero output impedance.

Output voltage

→ consider an ICVS amplifier.



→ exact equation for output voltage is

$$V_{out} = -\left(i_{in} R_f \frac{A_{VOL}}{1+A_{VOL}}\right)$$

as $A_{VOL} >> 1$ $\quad V_{out} = -i_{in} R_f \frac{\cancel{A_{VOL}}}{\cancel{A_{VOL}}}$

$$\boxed{V_{out} = -i_{in} R_f}$$

Non-inverting Input & output Impedances

→ The exact equations for closed-loop input & output impedance are

$$\boxed{Z_{in(CL)} = \frac{R_f}{1+A_{VOL}}} \qquad \boxed{Z_{out(CL)} = \frac{R_{out}}{1+A_{VOL}}}$$

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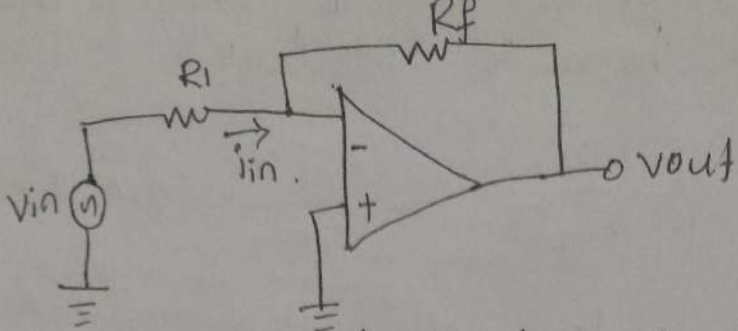
→ Large denomination will reduce the impedance to a very low value.

The inverting amplifier

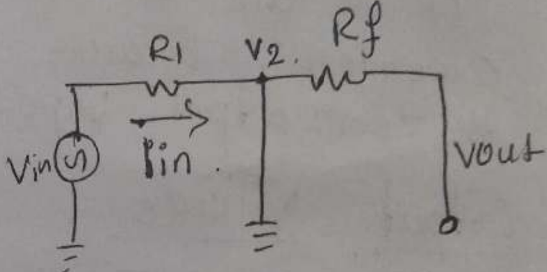


→ inverting amplifier has closed loop voltage gain

$$A_v = -\frac{R_f}{R_1}.$$

→ It uses ICVS negative feedback. Because of the virtual ground on the inverting input, the input current equals

$$i_{in} = \frac{V_{in}}{R_1}$$



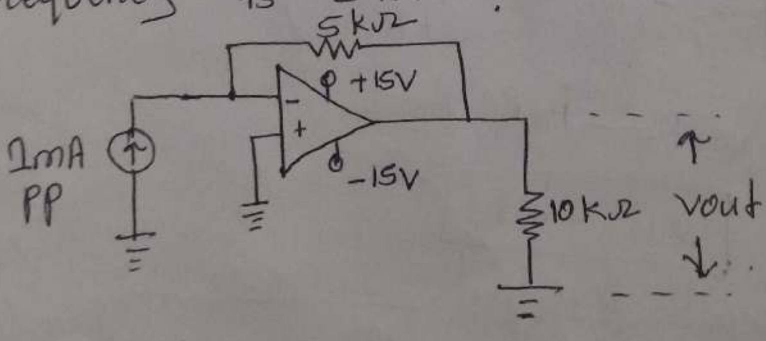
$$\frac{V_2 - V_{in}}{R_1} = i_{in}$$

$$V_2 = 0.$$

$$\frac{-V_{in}}{R_1} = i_{in}$$

$$i_{in} = \frac{-V_{in}}{R_1}. \quad //$$

Example - What is the output voltage if the input frequency is 1 kHz?



$$V_{out} = -i_{in} R_f.$$

$$= -1mA\,(5k\Omega)$$

$$= -5V_{pp}.$$

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* Practice the same with $R_f = 2k\Omega$.

Example - For the above circuit what are the closed-loop input and output impedance? Use 741C parameters.

$R_f = 5\,k\Omega$ $R_{out} = 75\,\Omega$

$A_{VOL} = 1,00,000$

$$Z_{in(CL)} = \frac{R_f}{1 + A_{VOL}} = \frac{5\,k\Omega}{1 + 100,000} \simeq \frac{5\,k\Omega}{1,00,000} = 0.05\,\Omega$$

$$Z_{out(CL)} = \frac{R_{out}}{1 + A_{VOL}} = \frac{75}{1 + 1,00,000} \simeq \frac{75}{1,00,000} = 0.00075\,\Omega$$

* Repeat the example with $A_{VOL} = 200,000$.

The VCIS amplifier

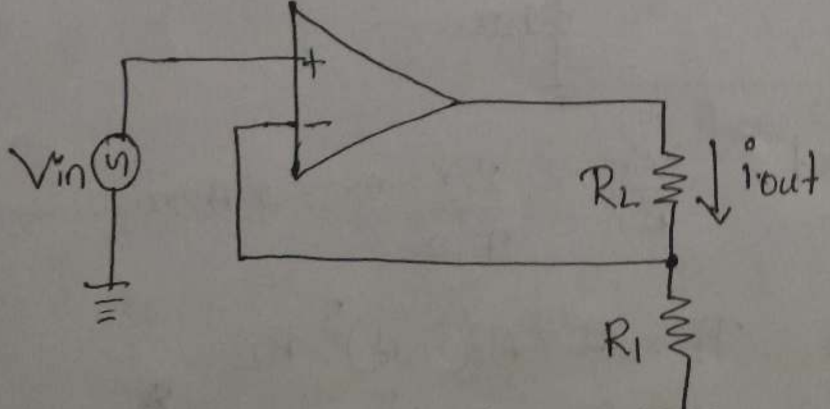
→ It converts an input voltage to a precise value of output current.

→ Fig shows VCIS amplifier. It is same as VCVS except R_L & feedback resistor R_1.

→ output is the current through R_2.

→ Output current is stabilized, exact equation for i_{out} is

$$\boxed{i_{out} = \frac{V_{in}}{R_1 + (R_1 + R_2)/A_{VOL}}}$$



VCIS amplifier.

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→ In a practical circuit, $(R_1 + R_2)/A_{VOL} \ll R_1$

$$\therefore \boxed{i_{out} = \frac{V_{in}}{R_1}}$$

also written as $\boxed{i_{out} = g_m v_{in}}$ where $g_m = \frac{1}{R_1}$

→ As the ~~output~~ input side of a VCIS is same as input side of VCVS amplifier the closed loop input impedance is given by

$$\boxed{Z_{in(CL)} = (1 + A_{VOL} B) R_{in}}$$

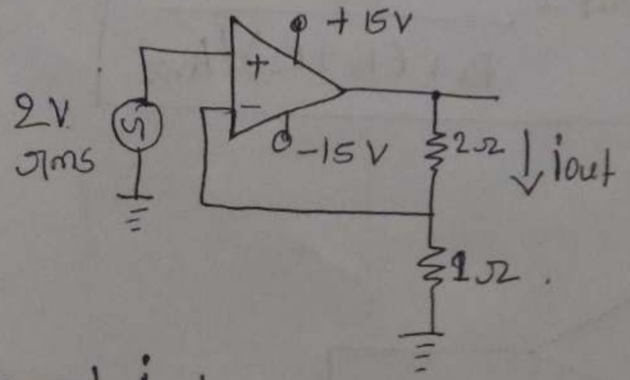
→ output impedance is given by

$$\boxed{Z_{out(CL)} = (1 + A_{VOL}) R_1}$$

→ The circuit is an almost perfect voltage to current converter because it has very high $Z_{in(CL)}$ & $Z_{out(CL)}$.

Example - what is the load current in fig? the load power? what happens if the load resistance changes to 4Ω?

Load



load current $i_{out} = \frac{V_{in}}{R_1} = \frac{2V_{rms}}{1\Omega} = 2\,A_{rms}$.

Load power $P_L = \cancel{I^2 R_L} (i_{out})^2 R_L$

$= (2\,A_{rms})^2\,(2\Omega)$

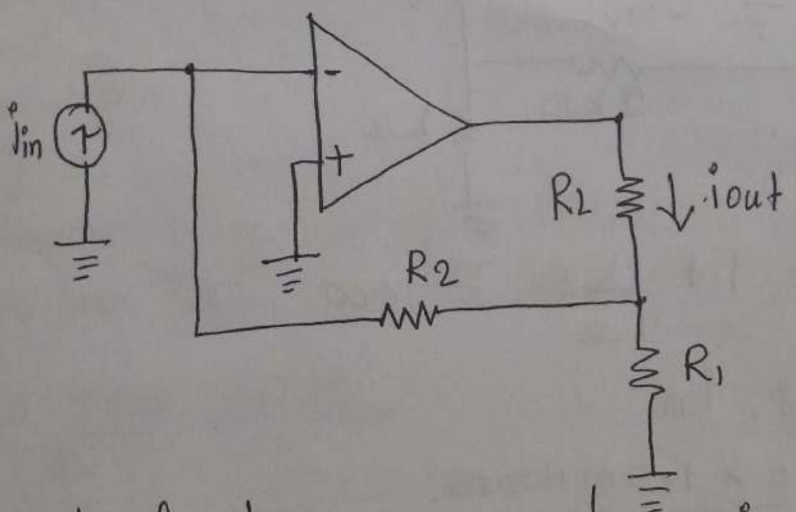
→ If load resistances changes to 4Ω

$$P_L = (i_{out})^2 R_L$$
$$= (2)^2 4$$
$$P_L = 16W$$

* Practice the problem by changing the input voltage to 3Vrms & solve for iout & P_L.

The ICIS amplifier.

→ It act as a perfect current amplifier.
→ It has heavy negative feedback.
→ It has low input impedance (Zin(CL)) & a very high output impedance Zout(CL).
→ Fig shows ICIS amplifier.



→ The closed-loop current gain is stabilized & given by

$$\boxed{A_i = \frac{A_{VOL}(R_1+R_2)}{R_L + A_{VOL}R_1}}$$

→ usually $A_{VOL}R_1 >> R_L$

$$\therefore \quad A_i = \frac{\cancel{A_{VOL}}(R_1+R_2)}{\cancel{A_{VOL}}R_1} = \frac{R_1}{R_1} + \frac{R_2}{R_1}$$

$$\boxed{A_i = 1 + \frac{R_2}{R_1}}$$

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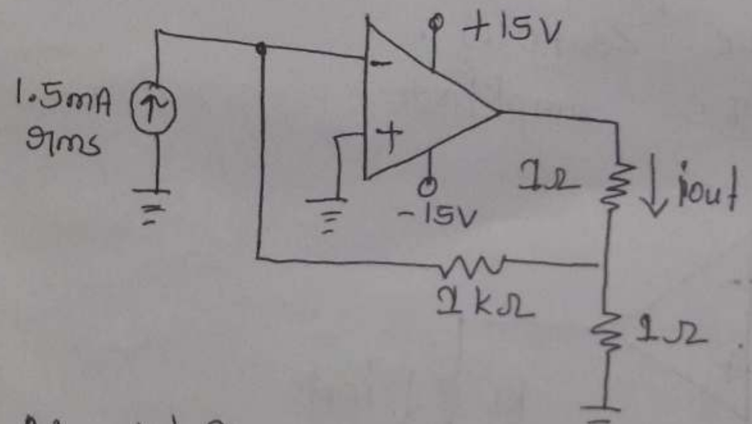
$$\boxed{Z_{in}(CL) = \frac{R_2}{1 + A_{VOL} B}}$$

feedback fraction B $\boxed{B = \frac{R_1}{R_1 + R_2}}$.

$$Z_{out}(CL) = (1 + A_{VOL}) R_1$$

→ Large A_{VOL} produces small Z_{in} & large Z_{out} so it acts as a perfect current amplifier.

Example - What is the load current in fig? the load power? If the load resistance is changed to 2Ω. what are the load current & power?



$$A_i = 1 + \frac{R_2}{R_1} = 1 + \frac{1k\Omega}{1\Omega} \cong 1000$$

$i_{out} = A_i \cdot i_{in}$

$= 1000 \times 1.5 mA\ rms$

$\boxed{i_{out} = 1.5\ A\ rms}$

Load power $P_L = (1.5\ A)^2 (1\Omega)$ — $i_{out}^2\ R_L$.

$\boxed{P_L = 2.25W}$

For $R_L = 2\Omega$.

$i_{out} = 1.5\ A$.

$P_L = (i_{out})^2 R_L$

$= (1.5 mA)^2\ 2\Omega$

$\boxed{P_L = 4.5 W}$

Practice - Using above fig change i_{in} to 2mA calculate i_{out} & P_L.

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Active Filters

→ A filter is an electronic circuit that passes one band of frequencies while rejecting other.

→ 2 types – Active filter, Passive filter.

Passive filter	Active filters
→ Built with R, L & C	→ Built with R, C & op-amp.
→ Used above 1 MHz	→ Useful below 1 MHz
→ Do not have power gain.	→ Have power gain.
→ Difficult to tune	→ Easy to tune

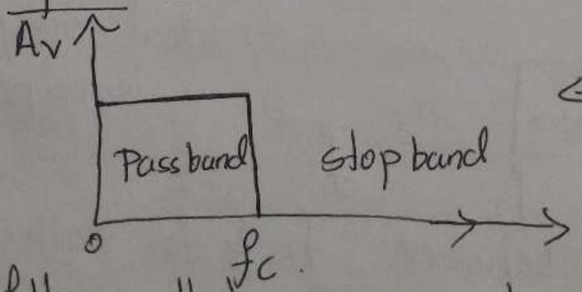
Ideal Responses

There are five types of filters.

1. Low-pass filter
2. High-pass "
3. Band-" "
4. Bandstop "
5. All pass "

Note- Frequency response of a filter is the graph of its voltage gain versus frequency.

1. Low Pass Filter.



← ideal lowpass filter.

→ The filter that passes lower frequences & stops higher frequency is called low pass filter.

→ It passes all the frequencies from zero to the cut of frequency 'fc' called pass band.

→ Blocks all frequencies above fc called stop band.

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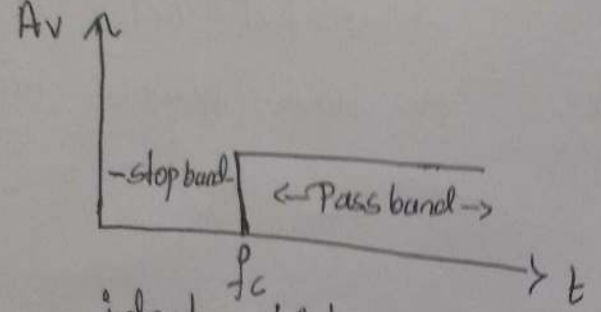
→ An ideal low-pass filter has zero attenuation (signal loss) in pass band. Infinite attenuation in the stopband & vertical attenuation. center

2. <u>High-pass filter</u>

→ A filter that passes the frequency above 'f_c' and stops the signal frequency below 'f_c' is called high-pass filter.



<u>ideal high-pass response</u>

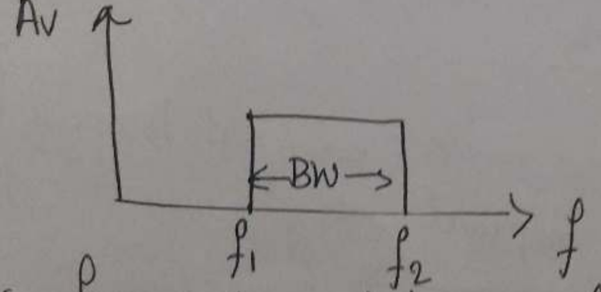
→ Blocks all frequencies from zero to f_c called <u>stop band</u>

→ Passes " " above f_c - called <u>pass band</u>

→ ideal HPF has infinite attenuation in stop band & zero attenuation in pass band & vertical attenuation.

3. <u>Band pass Filter</u>

A filter that passes all the frequencies between the lower & upper cutoff frequencies is called Band pass filter.



← ideal response of bandpass.

→ passes frequencies between f_1 & f_2 called pass band.

→ Blocks frequencies below f_1 (lower cut off) & above f_2 (higher cutoff) are called stop band.

→ $\boxed{\text{Band width} = f_2 - f_1}$

→ An ideal bandpass filter has zero attenuation in pass band, infinite attenuation in the stopband & two vertical transition.

ation → Center frequency $\boxed{f_0 = \sqrt{f_1 f_2}}$

$$\boxed{Q = \frac{f_0}{BW}}$$

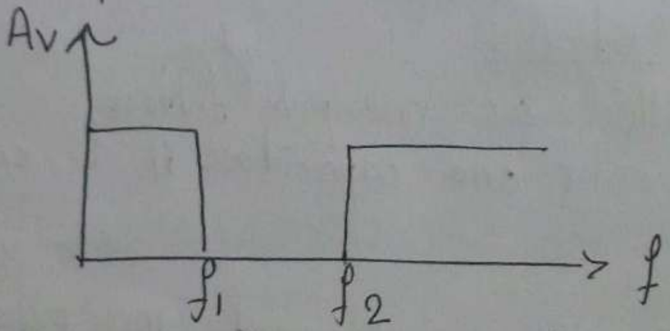
If $Q > 10$ $\quad f_0 \simeq \frac{f_1 + f_2}{2}$

→ If $Q < 1$ band pass filter is called wide band filter

→ If $Q > 1$ " " " " " Narrow " filter.

Band stop Filter

→ A filter that pases all frequencies from zero up to lower cutoff frequency & above upper cutoff frequency is called band stop filter.



Ideal response of BSF

→ 0 to f_1 & ~~the~~ or above f_2 is the pass band

→ f_1 to f_2 is the stop band

→ Ideal band stop filter has infinite attenuation in the stop band, no attenuation in the pass band & two vertical transition.

$$BW = f_2 - f_1$$

$$f_0 = \sqrt{f_1 f_2}$$

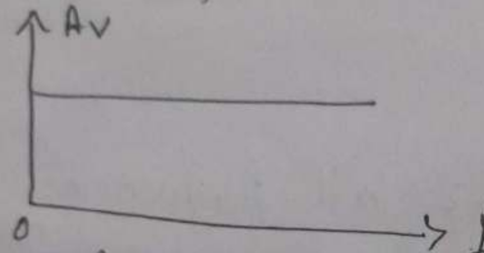
$$Q = \frac{f_0}{BW}$$

RK

→ It is sometimes called as notch filter because it notches out (removes) all frequencies in the stopband.

All-Pass Filter

→ A filter that passes all the frequency is called All pass filter.
→ It has passband and no stopband.
→ It passes all frequencies between zero & ∞ frequency.
→ Since it has zero attenuation for all frequencies it is called as filter.



→ In all pass filter, each frequency can be shifted by a certain amount as it passes through the filter.

First Order Stages

→ It is also called as one-pole active filter.
→ stages have only one capacitor it is called as 1st order.

Low-pass stages

→ Below are 3 ways to implement low pass stages.

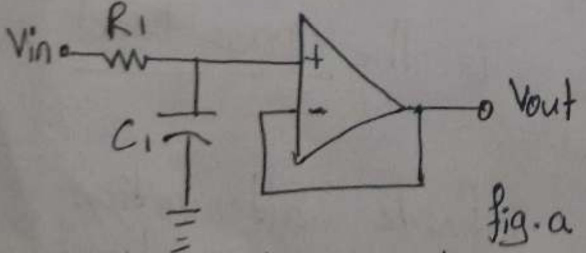


fig.a

$$A_v = 1.$$

$$f_c = \frac{1}{2\pi R_1 C_1}$$ (3-dB cutoff frequency)

Non inverting unity gain 1st order low pass filter.

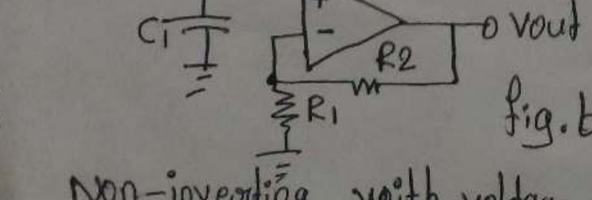


fig.b.

$$A_v = \frac{R_2}{R_1} + 1$$

$$f_c = \frac{1}{2\pi R_3 C_1}$$

Non-inverting with voltage gain 1st order LPF stage

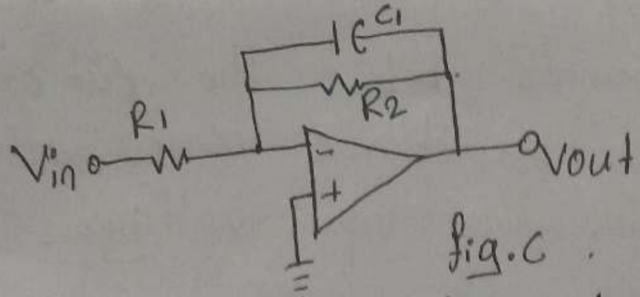


fig.c.

$A_v = \frac{-R_2}{R_1}$

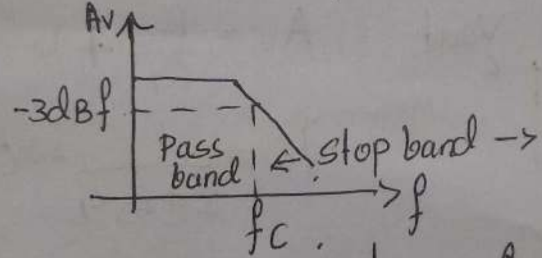
$f_c = \frac{1}{2\pi R_2 C_1}$

~~Non~~ Inverting with voltage gain 1st order LPF.

→ In fig.a as the frequency increases above cutoff frequency f_c. $X_c \downarrow$ decreases & reduces the non inverting input voltage.

→ So output is roll off after 'f_c'.

→ As frequency reaches '∞' capacitor becomes short & there is zero input voltage & zero output voltage.

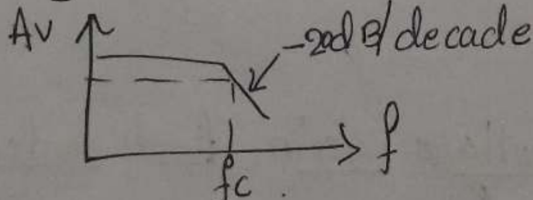


→ Fig.b shows non inverting first order lowpass filter.

→ It produces an voltage gain

$A_v = \frac{R_2}{R_1} + 1$.

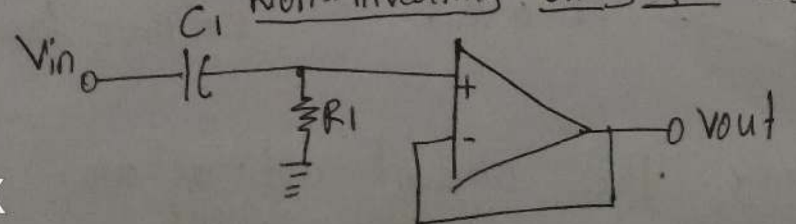
→ R_3C_1 lag circuit is outside the feedback loop, the output voltage rolls off at a rate of 20 dB per decade



High pass stage

→ There are 3 ways to implement high pass stages

1. Non-inverting unity gain highpass stage



Noninverting unity gain

$A_v = 1$. unity gain.

3dB cut off frequency

$f_c = \frac{1}{2\pi R_1 C_1}$.

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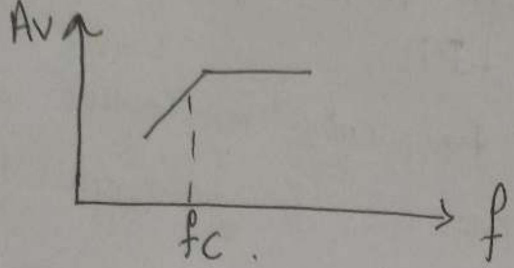
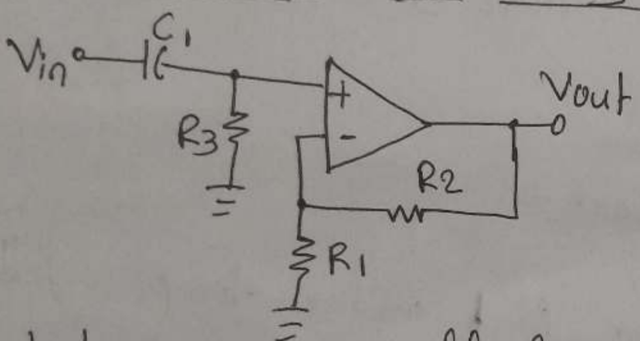
→ when frequency decreases below the cut off frequency. X_C → capacitive reactance increases. and reduces the non inverting input voltage. So output voltage rolls off.



→ As the frequency approaches zero, capacitor becomes open & there is zero input voltage.

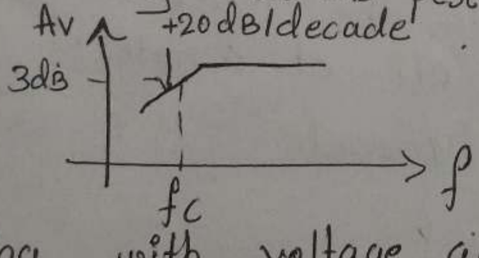
② Non-inverting with voltage gain high-pass stage.



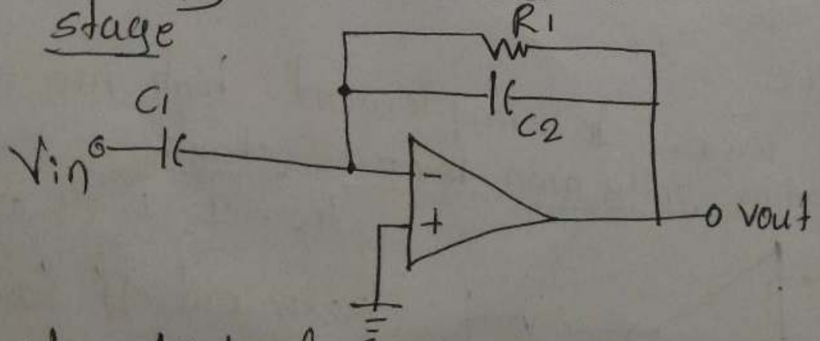
$A_V = \frac{R_2}{R_1} + 1$ Gain

$f_C = \frac{1}{2\pi R_3 C_1}$ 3dB cut off frequency.

→ below the cut off frequency R_3C_1 circuit reduces the non inverting input voltage. So output voltage starts ~~increasing~~ roll off 20 dB per decade



③ Inverting with voltage gain first order high pass stage



$A_V = \frac{-C_1}{C_2}$ gain

$f_C = \frac{1}{2\pi R_1 C_2}$ 3dB cutoff frequency.

→ At high frequency the circuit act as an inverting amplifier with a voltage gain of

$$\boxed{A_V = \frac{-X_{C2}}{X_{C1}} = \frac{-C_1}{C_2}}$$

$\frac{1}{X_{C1}} = C_1 \quad \frac{1}{X_{C2}} = C_2$

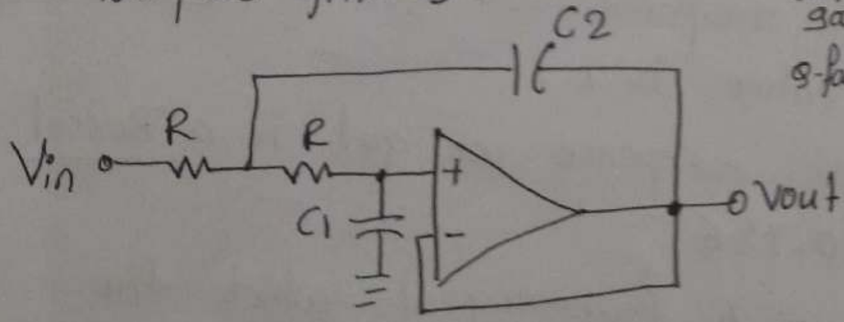
RK

→ As the frequency decreases. X_C ↑ & reduces the input signal & the feed back.
→ voltage gain also reduces.
→ As the frequency aproaches zero, the capacitor becomes open and there is no input signal.

VCVS Unity-Gain Second-Order Low-Pass Filters (LPF)

→ It is a second order or 2-pole filter.
→ called as sallen-key LPF (named after inventors).
→ called as VCVS filters because the op-amp is used as a voltage controlled voltage source.
→ VCVS LPF circuit can implement 3 basic aproximation: Butterworth, Chebyshev, and Bessel.

Second-order VCVS stage for Butterworth and Bessel (sallen key second order low pass filter).



unity gain → $A_V = 1$

Q-factor → $Q = 0.5 \sqrt{\frac{C_2}{C_1}}$

$f_p = \frac{1}{2\pi R \sqrt{C_1 C_2}}$

Butterworth
$Q = 0.707$
$K_c = 1$

Bessel
$Q = 0.577$
$K_c = 0.786$

→ In the circuit two resistors have same value But the two capacitors have different value.
→ Lag circuit is connected to non-inverting terminal feedback (output) is connected through capacitor C2.

→ when frequency is low both capacitors appear as open circuit.

→ Circuit is connected as a voltage follower ∴ $A_v =$

→ As when frequency increases, impedance of C_1 decreases & the noninverting input voltage decreases.

→ As C_2 is connected in the feedback provides the signal to the noninverting input which is inphase. So feedback signal adds the source signal, feedback is positive.

→ $C_2 > C_1$ to get positive feedback. It increases 'Q'.

Pole frequency - A special frequency used in the design of active filters. is called Pole frequency(f_p)

Pole frequency is given by $f_p = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$

as $R_1 = R_2 = R$.

$$\boxed{f_p = \frac{1}{2\pi R\sqrt{C_1C_2}}}$$

If $Q = 0.707$ the response we get is a butterworth response and kc value is 1.

If $Q = 0.577$, the response we get is a Bessel response & $k_c = 0.786$.

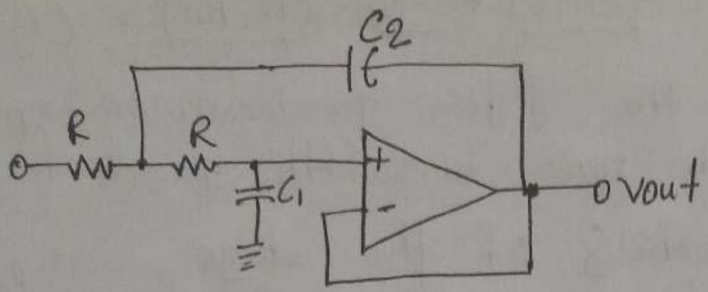
→ cut off frequency - A frequency at which the attenuation is 3dB is given by

$$\boxed{f_c = k_c f_p}$$

Second order VCVS stage for $Q > 0.707$. (Peaked response).

→ Fig analyze the circuit when $Q > 0.707$.

RK



$A_v = 1$

$Q = 0.5\sqrt{\frac{C_2}{C_1}}$

$f_p = \frac{1}{2\pi R\sqrt{C_1 C_2}}$

$Q > 0.707$

$f_0 = k_0 f_p$

$f_c = k_c f_p$

$f_{3dB} = k_3 f_p$.

→ Resonanant frequency where peaking appears

$$\boxed{f_0 = k_0 f_p}$$

→ Edge frequency

$f_c = k_c f_p$.

→ 3dB frequency

$f_{3dB} = k_3 f_p$.

→ For $Q > 10$.

$k_0 = 1$

$k_c = 1.414$

$k_3 = 1.55$

$A_p = 20 \log Q$

RK

Gain-Bandwidth product of op Amps (GBW)

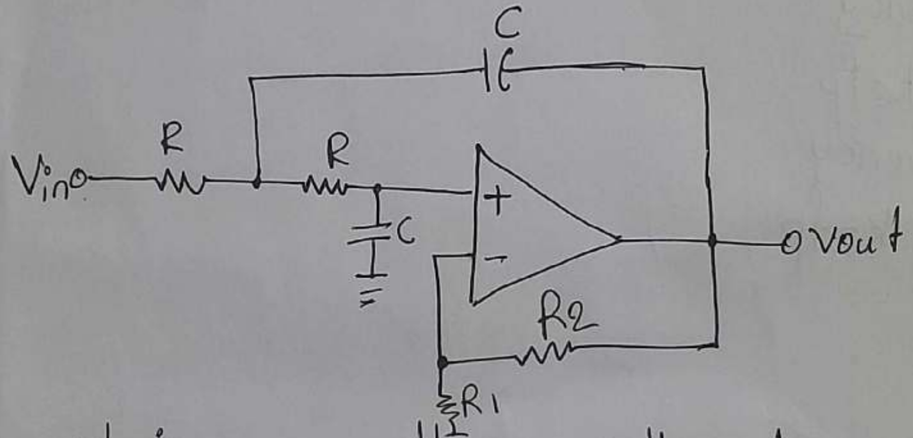
→ Not to affect the filter performance op-amps must have enough gain-bandwidth product (GBW).

→ Limited GBW (increase) Q of the stage

→ " " change performance of a filter.

→ Using Predistortion method limited GBW can be corrected.

VCVS Equal-component Low pass filters.



$$A_V = \frac{R_2}{R_1} + 1$$

$$Q = \frac{1}{3 - A_V}$$

$$f_p = \frac{1}{2\pi RC}.$$

→ It is an another sallen-key second order low-pass filter.

→ It uses same values of 'R' & same values of 'C'.

→ This is why the circuit called a sallen-key equal component filter.

→ Voltage gain of the circuit is $A_V = \frac{R_2}{R_1} + 1$.

→ Q of the circuit is $Q = \frac{1}{3 - A_V}$.

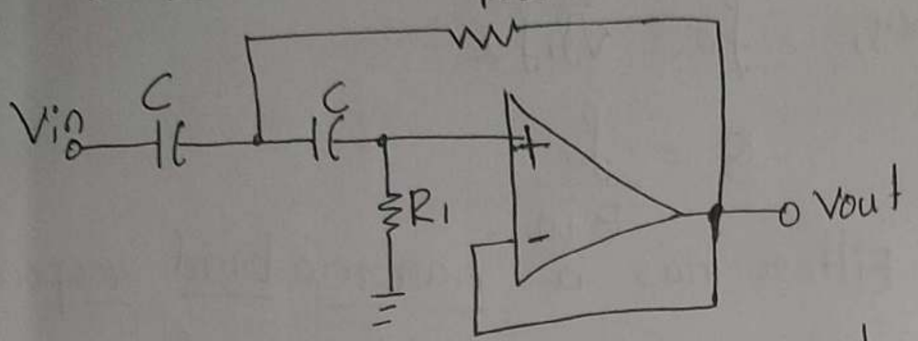
→ Condition is A_V can be no smaller than unity (1 to 3) & minimum Q is 0.5 V

→ when $A_V > 3$. positive feedback becomes too large and it breaks in to oscillation. When A_V approaches 3 component tolerance & drift causes A_V to exceed 3.

VCVS High-Pass filters

There are two configuration.

① Second order VCVS high-pass ~~filter~~ stages - unity gain.



$A_v = 1$

$Q = 0.5\sqrt{\dfrac{R_1}{R_2}}$

$f_p = \dfrac{1}{2\pi C\sqrt{R_1R_2}}$

→ Fig shows the sallen-key unity gain high pass filter and its equation.

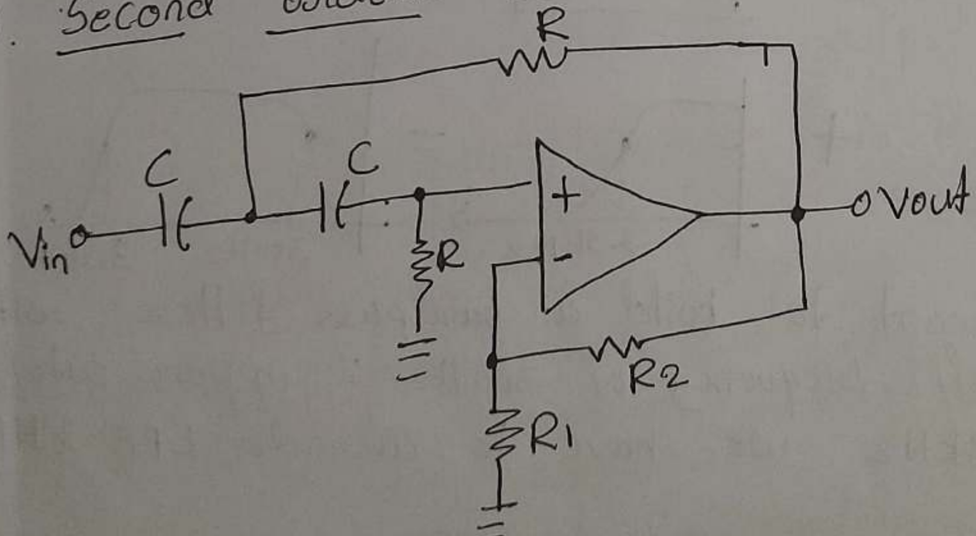
→ Here position of R & C are reversed.

→ Q depends on value of R.

→ cut off frequency of a high pass filter

$$f_c = \frac{f_p}{K_c}.$$

② Second order VCVS high pass stages - voltage gain



$A_v = \dfrac{R_2}{R_1} + 1$

$Q = \dfrac{1}{3 - A_v}$

$f_p = \dfrac{1}{2\pi RC}$.

→ Fig shows the sallen-key equal component high pass filter and its equation.

RK

MFB Bandpass Filters.

→ A band pass filter has a center frequency & a bandwidth.

Band width, $BW = f_2 - f_1$

center frequency, $f_0 = \sqrt{f_1 f_2}$.

$$Q = \frac{f_0}{BW}.$$

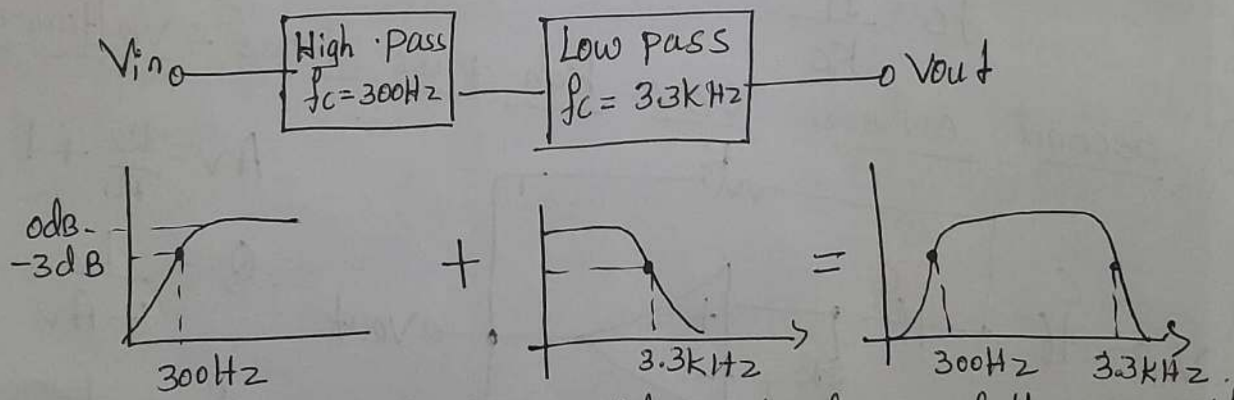
When $Q > 1$ Filter has a narrow band response

" $Q < 1$ " " " Wide band response

Wide Band Filters

→ when $Q < 1$ Filter has a wide band response

→ we can construct wide band filter by cascading low-pass & high pass stages.



→ suppose we want to build a bandpass filter with a lower cutoff frequency of 300 Hz & upper cutoff frequency 3.3kHz. we have to cascade LPF & HPF as above.

$$f_0 = \sqrt{f_1 f_2} = \sqrt{(300\,Hz)(3.3\,kHz)} = 995\,Hz$$

$$BW = f_2 - f_1 = 3.3\,kHz - 300\,Hz = 3\,kHz.$$

$$Q = \frac{f_0}{BW} = \frac{995}{3\,kHz} = 0.332.$$

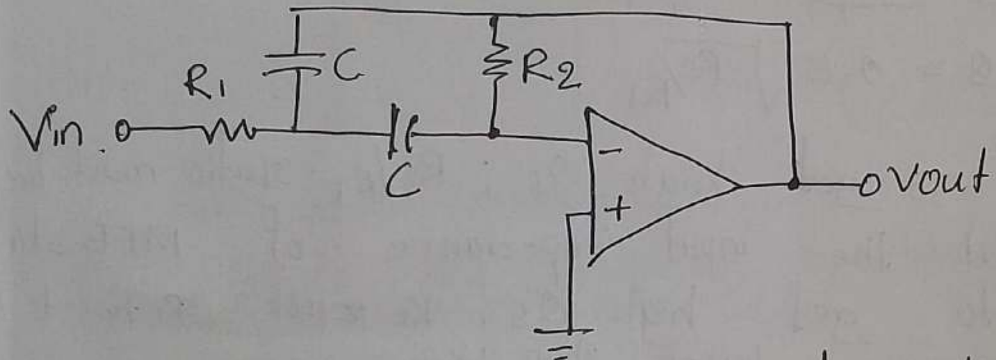
Q is less than 1.

RK

-> HPF has a ~~cut~~ $f_C = 300\,Hz$.
-> LPF " " $f_C = 3.3\,kHz$.
-> when we add the responses we get bandpass filter with cutoff frequencies of 300Hz & 3.3kHz.

Narrow band Filters (Multiple feedback (MFB)).

-> when $Q > 1$. multiple - feedback filter is used.



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

$$Q = 0.5\sqrt{\frac{R_2}{R_1}}$$

$$f_0 = \frac{1}{2\pi C\sqrt{R_1R_2}}.$$

-> Vin is given to the inverting terminal.
-> Circuit has two feedback path one through 'C' & another through 'R_2'
-> At lower frequencies (when f is low) capacitor act as open switch. Therefore input signal cannot reach the opamp and the output is zero.
-> At high frequency (when f is high) capacitor act as a closed switch. so voltage gain is zero as capacitor has zero impedance.
-> Between extremes low and high frequency, there is a band of frequencies where the circuit acts like an inverting amplifier.

voltage gain at the center frequency is given by $A_V = \frac{-R_2}{2R_1}$.

Q of the circuit is given by

$$Q = 0.5\sqrt{\frac{R_2}{R_1}}$$

$$Q = 0.707 * \sqrt{-A_V}$$

If $A_v = -100$

$Q = 0.707\sqrt{100} = 7.07$.

→ Greater the voltage gain higher the Q.

$$f_0 = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} \quad \text{Since } C_1 = C_2$$

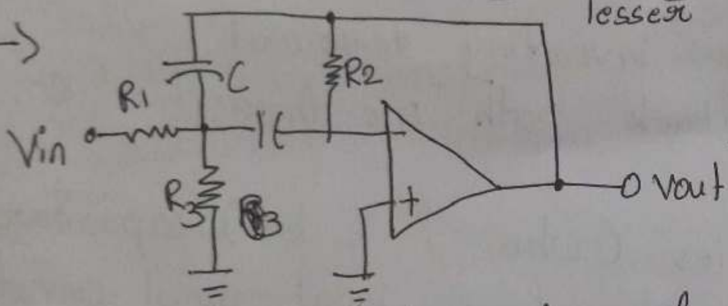
$$f_0 = \frac{1}{2\pi C\sqrt{R_1R_2}}$$

Increasing the input Impedance.

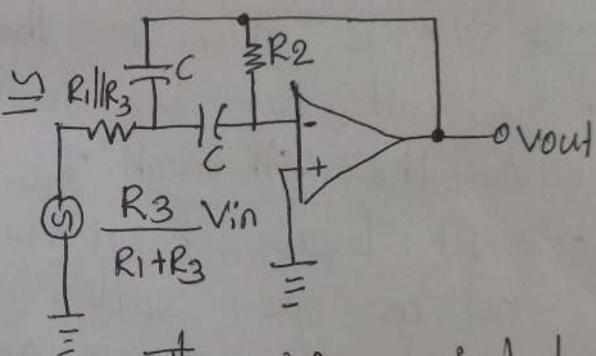
We have $Q = 0.5\sqrt{R_2/R_1}$.

→ $Q \propto R_2/R_1$, To get high Qs; R_2/R_1 ratio must be kept high. But the input impedance of MFB stage is too low to get high Qs. R_2 ~~=~~ 100k Ω, R_1 has to be lesser than 1kΩ

→



Increasing input impedance of MFB stage



Thevenin's equivalent circuit

→ Fig shows an MFB bandpass filter that increases the input impedance. Extra resistor R_3 is used to divide the voltage.

Voltage gain $A_v = \frac{-R_2}{2R_1}$.

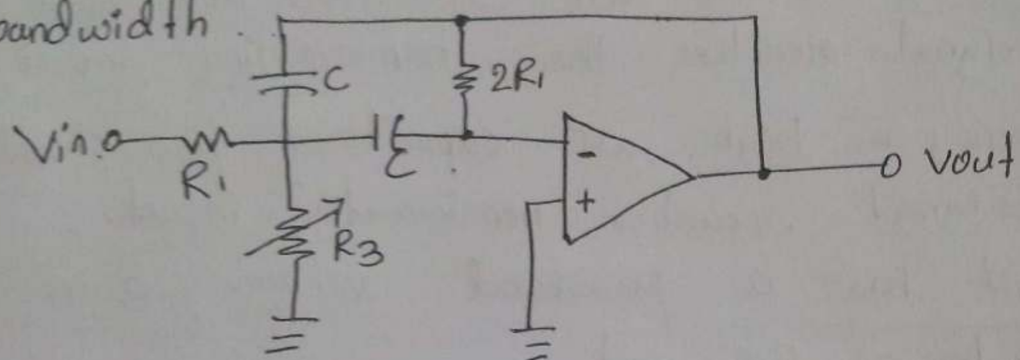
Q factor $Q = 0.5\sqrt{\frac{R_2}{R_1 || R_3}}$

$$f_0 = \frac{1}{2\pi C\sqrt{(R_1||R_3)R_2}}.$$

RK

Tunable center Frequency with constant Bandwidth.

→ Fig shows the modified circuit that has $A_v = 1$ & ~~mat~~ has a variable center frequency and constant bandwidth.



→ In the above circuit, $R_2 = 2R_1$ & R_3 is variable. The circuit has following equations.

$$A_v = -1$$

$$Q = 0.707\sqrt{\frac{R_1+R_3}{R_3}}$$

$$f_o = \frac{1}{2\pi C\sqrt{2R_1(R_1 \| R_3)}}$$

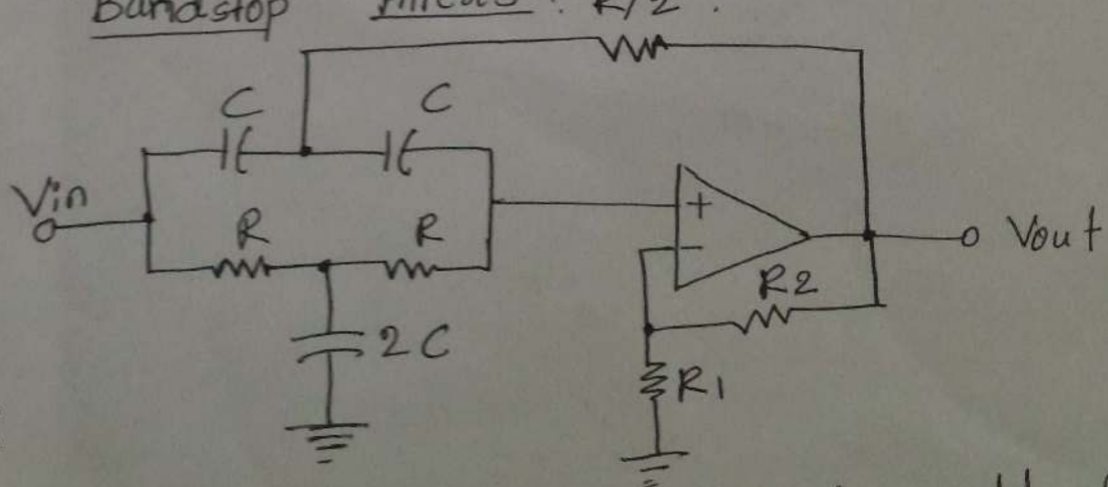
f_o depends on R_3
R_3 changes center frequency
f_o changes.

Since $BW = \frac{f_o}{Q}$

$$BW = \frac{1}{2\pi R_1 C}.$$

BW does not depends on R_3
∴ even though R_3 changes BW remains constant.

Bandstop Filters.



Sallen-key second-order notch filter

→ Fig shows a Sallen-key second order notch filter & its equations. 82

→ Bandstop filter block only a single frequency (notch filter)

→ when frequency is low all capacitors are open, all input signal reaches the non inverting input.

→ when frequency is high, all capacitors are shorted, all input signal reaches non inverting input.

→ the circuit has a passband voltage gain

$$\boxed{A_v = \frac{R_2}{R_1} + 1}$$

→ Center frequency (f_0) is between extreme low & high frequency.

$$\boxed{f_0 = \frac{1}{2\pi RC}}$$

→ At f_0 feedback signal returns with the correct amplitude and phase to attenuate the signal on the non-inverting input.

→ The Q of the circuit

$$\boxed{Q = \frac{0.5}{2 - A_v}}$$

→ $A_v < 2$ to avoid oscillations. & Q must be less than 10.

RK

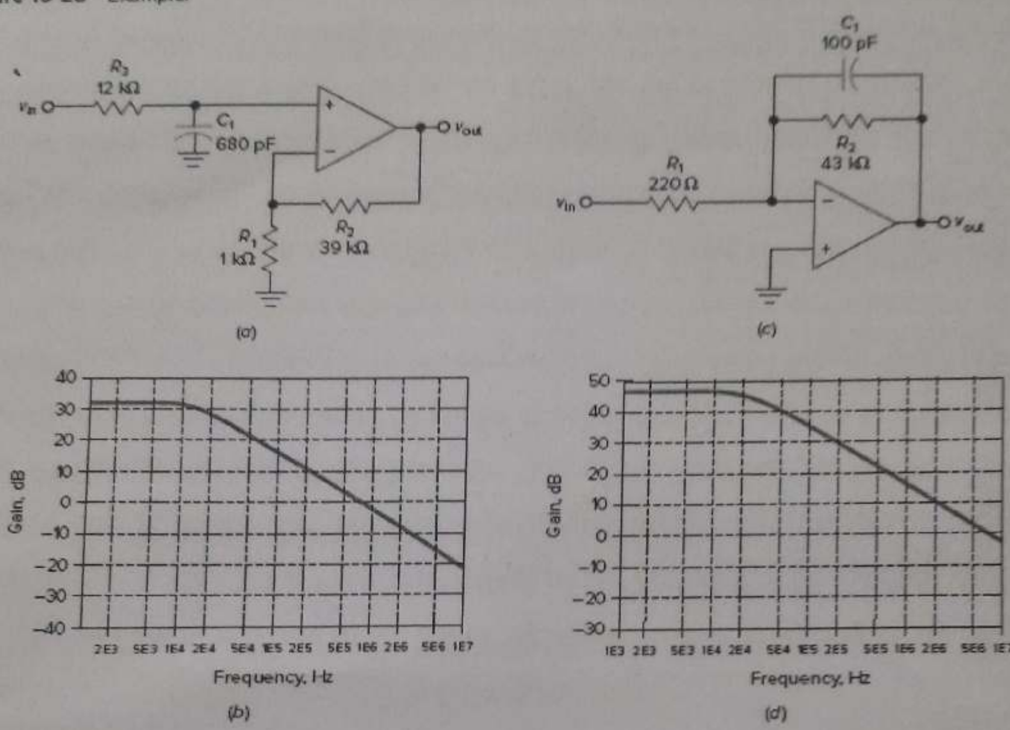
First Order stages.

Example 19-1

What is the voltage gain in Fig. 19-23*a*? What is the cutoff frequency? What is the frequency response?

Figure 19-23 Example.

(1)



SOLUTION This is a noninverting first-order low-pass filter. With Eqs. (19-10) and (19-11), the voltage gain and cutoff frequencies are:

$$A_V = \frac{39\text{ k}\Omega}{1\text{ k}\Omega} + 1 = 40 \qquad [1 + R_f/R_1]$$

$$f_c = \frac{1}{2\pi(12\text{ k}\Omega)(680\text{ pF})} = 19.5\text{ kHz} \qquad \frac{1}{2\pi R_3 C_1}$$

Figure 19-23*b* shows the frequency response. The voltage gain is 32 dB in the passband. The response breaks at 19.5 kHz and then rolls off at a rate of 20 dB per decade.

PRACTICE PROBLEM 19-1 Using Fig. 19-23*a*, change the 12-kΩ resistor to 6.8 kΩ. Find the new cutoff frequency.

Example 19-2

(2)

What is the voltage gain in Fig. 19-23*c*? What is the cutoff frequency? What is the frequency response?

SOLUTION This is an inverting first-order low-pass filter. With Eqs. (19-12) and (19-13), the voltage gain and cutoff frequencies are:

$$A_V = \frac{-43\text{ k}\Omega}{220\ \Omega} = -195 \qquad -\frac{R_f}{R_1}$$

$$f_c = \frac{1}{2\pi(43\text{ k}\Omega)(100\text{ pF})} = 37\text{ kHz} \qquad \frac{1}{2\pi R_2 C_1}$$

Figure 19-23*d* shows the frequency response. The voltage gain is 45.8 dB in the passband. The response breaks at 37 kHz and then rolls off at a rate of 20 dB per decade.

RK PRACTICE PROBLEM 19-2 In Fig. 19-23*c*, change the 100-pF capacitor to 220 pF. What is the new cutoff frequency?

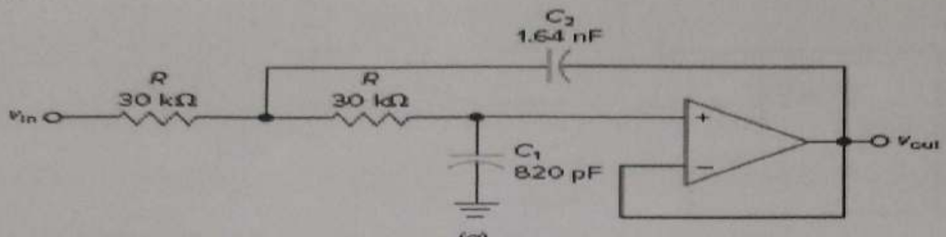
Second order stages

Application Example 19-3

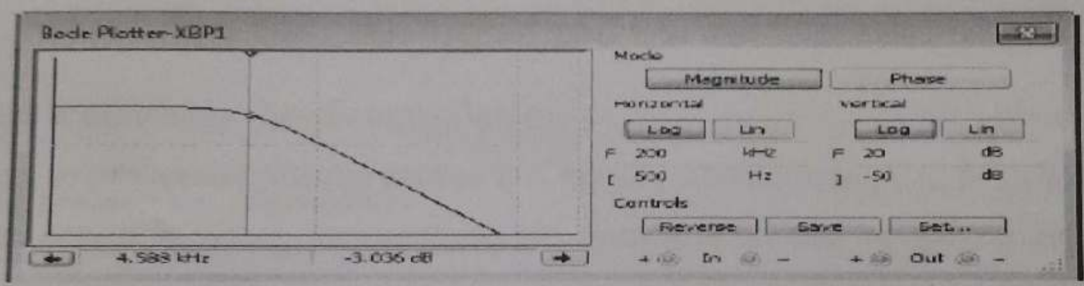
MultiSim

What are the pole frequency and Q of the filter shown in Fig. 19-27? What is the cutoff frequency? Show the frequency response using a Multisim Bode plotter.

Figure 19-27 (a) Butterworth unity-gain example; (b) Multisim frequency response.



(a)



(b)

Courtesy of National Instruments.

SOLUTION The Q and pole frequency are:

$$Q = 0.5\sqrt{\frac{C_2}{C_1}} = 0.5\sqrt{\frac{1.64\text{ nF}}{820\text{ pF}}} = 0.707$$

$$f_p = \frac{1}{2\pi R\sqrt{C_1C_2}} = \frac{1}{2\pi(30\text{ k}\Omega)\sqrt{(820\text{ pF})(1.64\text{ nF})}} = 4.58\text{ kHz}$$

The Q value of 0.707 tells us that this is a Butterworth response, so the cutoff frequency is the same as the pole frequency:

$$f_c = f_p = 4.58\text{ kHz}$$

$f_c = k_c f_p$.

The response of the filter breaks at 4.58 kHz and rolls off at a rate of 40 dB per decade because $n = 2$. Figure 19-27b shows the Multisim frequency response plot.

PRACTICE PROBLEM 19-3 Repeat Application Example 19-3 with the resistor values changed to 10 kΩ.

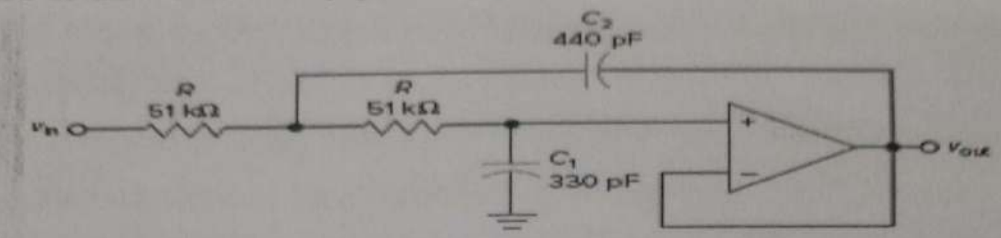
RK

second order LPF.

Example 19-4

In Fig. 19-28, what are the pole frequency and Q? What is the cutoff frequency?

Figure 19-28 Bessel unity-gain example.



SOLUTION The Q and pole frequency are:

$$Q = 0.5\sqrt{\frac{C_2}{C_1}} = 0.5\sqrt{\frac{440\text{ pF}}{330\text{ pF}}} = 0.577$$

$$f_p = \frac{1}{2\pi R\sqrt{C_1C_2}} = \frac{1}{2\pi(51\text{ k}\Omega)\sqrt{(330\text{ pF})(440\text{ pF})}} = 8.19\text{ kHz}$$

The Q value of 0.577 tells us that this is a Bessel response. With Eq. (19-21), the cutoff frequency is given by:

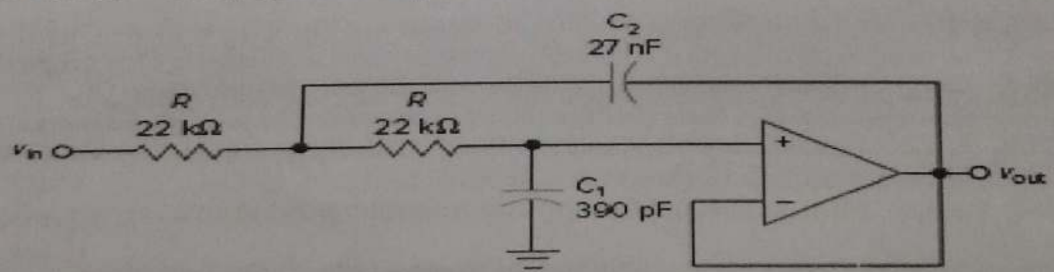
$$f_c = K_c f_p = 0.786(8.19\text{ kHz}) = 6.44\text{ kHz}$$

PRACTICE PROBLEM 19-4 In Example 19-4, if the value of C_1 changed to 680 pF, what value should C_2 be to maintain a Q of 0.577?

Example 19-5

What are the pole frequency and Q in Fig. 19-29? What are the cutoff and 3-dB frequencies?

Figure 19-29 Unity-gain example with $Q > 0.707$.



SOLUTION The Q and pole frequency are:

$$Q = 0.5\sqrt{\frac{C_2}{C_1}} = 0.5\sqrt{\frac{27\text{ nF}}{390\text{ pF}}} = 4.16$$

$$f_p = \frac{1}{2\pi R\sqrt{C_1C_2}} = \frac{1}{2\pi(22\text{ k}\Omega)\sqrt{(390\text{ pF})(27\text{ nF})}} = 2.23\text{ kHz}$$

Referring to Fig. 19-26, we can read the following approximate K and A_p values:

$K_0 = 0.99$ //
$K_c = 1.38$
$K_3 = 1.54$
$A_p = 12.5$ dB

The cutoff or edge frequency is:

$$f_c = K_c f_p = 1.38(2.23\text{ kHz}) = 3.08\text{ kHz}$$

and the 3-dB frequency is:

$$f_{3dB} = K_3 f_p = 1.54(2.23\text{ kHz}) = 3.43\text{ kHz}$$

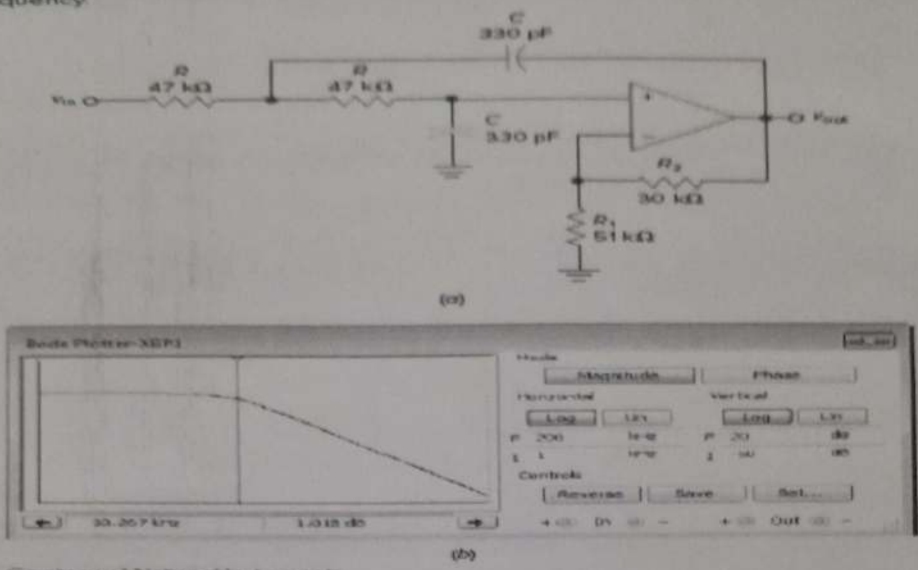
RK

PRACTICE PROBLEM 19-5 In Fig. 19-29, change the 27-nF capacitor to 14 nF and repeat Example 19.5.

Application Example 19-6

What are the pole frequency and Q of the filter shown in Fig. 19-32? What is the cutoff frequency? Show the frequency response using a Multisim Bode plotter.

Figure 19-32 (a) Butterworth equal-component example; (b) Multisim pole frequency



Courtesy of National Instruments

SOLUTION The A_V, Q, and f_p are:

$$A_V = \frac{30\ \text{k}\Omega}{51\ \text{k}\Omega} + 1 = 1.59$$

$$Q = \frac{1}{3 - A_V} = \frac{1}{3 - 1.59} = 0.709$$

$$f_p = \frac{1}{2\pi RC} = \frac{1}{2\pi(47\ \text{k}\Omega)(330\ \text{pF})} = 10.3\ \text{kHz}$$

It takes a Q of 0.77 to produce a ripple of 0.1 dB. Therefore, a Q of 0.709 produces a ripple of less than 0.003 dB. For all practical purposes, the calculated Q of 0.709 means that we have a Butterworth response to a very close approximation.

The cutoff frequency of a Butterworth filter is equal to the pole frequency of 10.3 kHz. Notice in Fig. 19-32*b* that the pole frequency is at approximately 1 dB. This value is 3 dB down from the passband gain of 4 dB.

PRACTICE PROBLEM 19-6 In Application Example 19-6, change the 47-kΩ resistors to 22 kΩ and solve for A_V, Q, and f_p.

Example 19-7

In Fig. 19-33, what are the pole frequency and Q? What is the cutoff frequency?

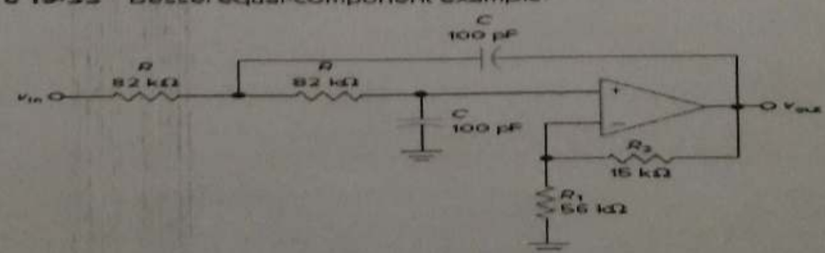
SOLUTION The A_V, Q, and f_p are:

$$A_V = \frac{15\ \text{k}\Omega}{56\ \text{k}\Omega} + 1 = 1.27$$

$$Q = \frac{1}{3 - A_V} = \frac{1}{3 - 1.27} = 0.578$$

$$f_p = \frac{1}{2\pi RC} = \frac{1}{2\pi(82\ \text{k}\Omega)(100\ \text{pF})} = 19.4\ \text{kHz}$$

Figure 19-33 Bessel equal-component example



RK

This is the Q of a Bessel second-order response. Therefore, $K_c = 0.786$ and the cutoff frequency is:

$$f_c = 0.786 f_p = 0.786(19.4 \text{ kHz}) = 15.2 \text{ kHz}$$

PRACTICE PROBLEM 19-7 Repeat Example 19-7 with the capacitors equal to 330 pF and the R value set to 100 kΩ.

Example 19-8

What are the pole frequency and Q in Fig. 19-34? What are the resonant, cutoff, and 3-dB frequencies? What is the ripple depth in decibels?

SOLUTION The A_V, Q, and f_p are:

$$A_V = \frac{39 \text{ k}\Omega}{20 \text{ k}\Omega} + 1 = 2.95$$

$$Q = \frac{1}{3 - A_V} = \frac{1}{3 - 2.95} = 20$$

$$f_p = \frac{1}{2\pi RC} = \frac{1}{2\pi(56 \text{ k}\Omega)(220 \text{ pF})} = 12.9 \text{ kHz}$$

Figure 19-26 has Qs only between 1 and 10. In this case, we need to use Eqs. (19-25) through (19-28) to get the K and Q values:

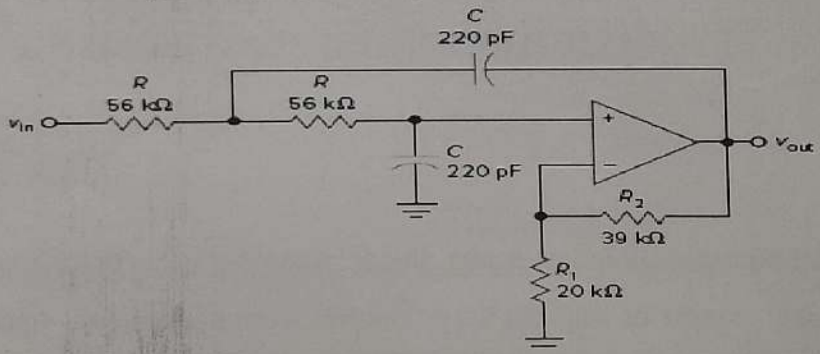
$$K_0 = 1$$

$$K_c = 1.414$$

$$K_3 = 1.55$$

$$A_p = 20 \log Q = 20 \log 20 = 26 \text{ dB}$$

Figure 19-34 Equal-component example with $Q > 0.707$.



The resonant frequency is:

$$f_0 = K_0 f_p = 12.9 \text{ kHz}$$

The cutoff or edge frequency is:

$$f_c = K_c f_p = 1.414\,(12.9 \text{ kHz}) = 18.2 \text{ kHz}$$

and the 3-dB frequency is:

$$f_{3dB} = K_3 f_p = 1.55(12.9 \text{ kHz}) = 20 \text{ kHz}$$

The circuit produces a 26-dB peak in the response at 12.9 kHz, rolls off to 0 dB at the cutoff frequency, and is down 3 dB at 20 kHz.

A Sallen-Key circuit like this is impractical because the Q is too high. Since the voltage gain is 2.95, any error in the values of R_1 and R_2 can cause large increases in Q. For instance, if the tolerance of the resistors is ±1 percent, the voltage gain can be as high as:

$$A_V = \frac{1.01(39 \text{ k}\Omega)}{0.99(20 \text{ k}\Omega)} + 1 = 2.989$$

This voltage gain produces a Q of:

$$Q = \frac{1}{3 - A_V} = \frac{1}{3 - 2.989} = 90.9$$

The Q has changed from a design value of 20 to an approximate value of 90.9, which means that the frequency response is radically different from the intended response.

Even though the Sallen-Key equal-component filter is simple compared to other filters, it has the disadvantage of component sensitivity when high Qs are used. This is why more complicated circuits are typically used for high-Q stages. The added complexity reduces the component sensitivity.

RK

Application Example 19-9

MultiSim

What are the pole frequency and Q of the filter shown in Fig. 19-36a? What is the cutoff frequency? Show the frequency response using a Multisim Bode plotter.

SOLUTION The Q and pole frequency are:

$$Q = 0.5\sqrt{\frac{R_1}{R_2}} = 0.5\sqrt{\frac{24\ \text{k}\Omega}{12\ \text{k}\Omega}} = 0.707$$

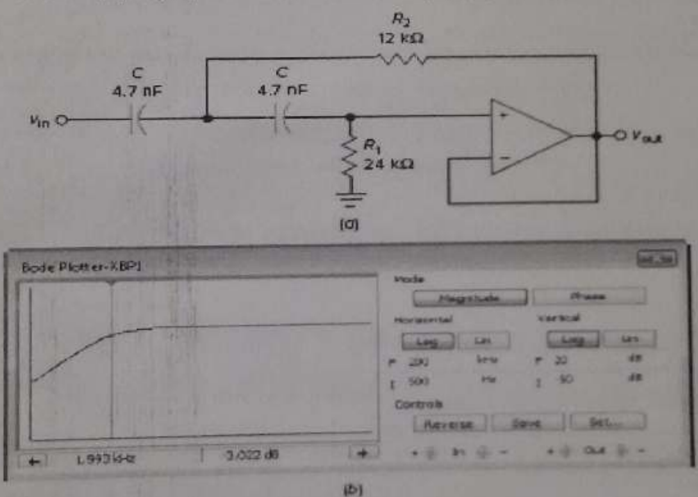
$$f_p = \frac{1}{2\pi C\sqrt{R_1R_2}} = \frac{1}{2\pi(4.7\ \text{nF})\sqrt{(24\ \text{k}\Omega)(12\ \text{k}\Omega)}} = 2\ \text{kHz}$$

Since $Q = 0.707$, the filter has a Butterworth second-order response and:

$$f_c = f_p = 2\ \text{kHz}$$

The filter has a high-pass response with a break at 2 kHz, and it rolls off at 40 dB per decade below 2 kHz. Figure 19-36(b) shows the Multisim frequency response plot.

Figure 19-36 (a) High-pass Butterworth example; (b) Multisim cutoff frequency.



Courtesy of National Instruments

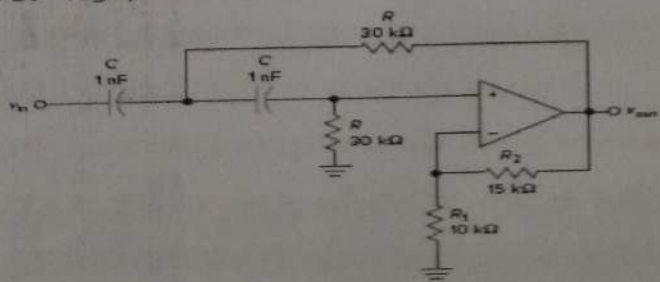
HW

PRACTICE PROBLEM 19-9 In Fig. 19-36, double the two resistor values. Find the circuit's Q, f_p, and f_c values.

Example 19-10

What are the pole frequency and Q in Fig. 19-37? What are the resonant, cutoff, and 3-dB frequencies? What is the ripple depth or peaking in decibels?

Figure 19-37 High-pass example with $Q > 1$.



SOLUTION The A_V, Q, and f_p are:

$$A_V = \frac{15\ \text{k}\Omega}{10\ \text{k}\Omega} + 1 = 2.5$$

$$Q = \frac{1}{3 - A_V} = \frac{1}{3 - 2.5} = 2$$

$$f_p = \frac{1}{2\pi RC} = \frac{1}{2\pi(30\ \text{k}\Omega)(1\ \text{nF})} = 5.31\ \text{kHz}$$

RK

In Fig. 19-26, a Q of 2 gives the following approximate values:

$K_0 = 0.94$
$K_c = 1.32$
$K_3 = 1.48$
$A_p = 20 \log Q = 20 \log 2 = 6.3$ dB

The resonant frequency is:

$$f_0 = \frac{f_p}{K_0} = \frac{5.31 \text{ kHz}}{0.94} = 5.65 \text{ kHz}$$

The cutoff frequency is:

$$f_c = \frac{f_p}{K_c} = \frac{5.31 \text{ kHz}}{1.32} = 4.02 \text{ kHz}$$

The 3-dB frequency is:

$$f_{3\text{dB}} = \frac{f_p}{K_3} = \frac{5.31 \text{ kHz}}{1.48} = 3.59 \text{ kHz}$$

The circuit produces a 6.3-dB peak in the response at 5.65 kHz, rolls off to 0 dB at the cutoff frequency of 4.02 kHz, and is down 3 dB at 3.59 kHz.

HW

PRACTICE PROBLEM 19-10 Repeat Example 19-10 with the 15-kΩ resistor changed to 17.5 kΩ.

Example 19-11

The gate voltage of Fig. 19-42 can vary the JFET resistance from 15 to 80 Ω. What is the bandwidth? What are the minimum and maximum center frequencies?

SOLUTION Equation (19-42) gives the bandwidth:

$$\text{BW} = \frac{1}{2\pi R_1 C} = \frac{1}{2\pi(18 \text{ k}\Omega)(8.2 \text{ nF})} = 1.08 \text{ kHz}$$

With Eq. (19-41), the minimum center frequency is:

$$f_0 = \frac{1}{2\pi C\sqrt{2R_1(R_1 \parallel R_3)}}$$

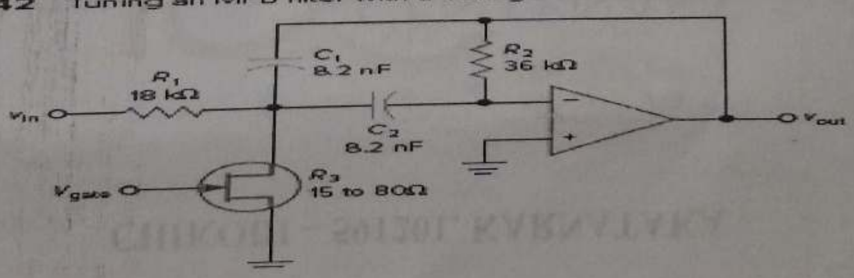
$$= \frac{1}{2\pi(8.2 \text{ nF})\sqrt{2(18 \text{ k}\Omega)(18 \text{ k}\Omega \parallel 80 \, \Omega)}}$$

$$= 11.4 \text{ kHz}$$

The maximum frequency is:

$$f_0 = \frac{1}{2\pi(8.2 \text{ nF})\sqrt{2(18 \text{ k}\Omega)(18 \text{ k}\Omega \parallel 15 \, \Omega)}} = 26.4 \text{ kHz}$$

Figure 19-42 Tuning an MFB filter with a voltage-controlled resistance.



PRACTICE PROBLEM 19-11 Using Fig. 19-42, change R_1 to 10 kΩ, change R_2 to 20 kΩ, and repeat Example 19-11.

Example 19-12

What are the voltage gain, center frequency, and Q for the bandstop filter shown in Fig. 19-43 if $R = 22$ kΩ, $C = 120$ nF, $R_1 = 13$ kΩ, and $R_2 = 10$ kΩ?

SOLUTION With Eqs. (19-43) through (19-45):

$$A_V = \frac{10 \text{ k}\Omega}{13 \text{ k}\Omega} + 1 = 1.77$$

$$f_0 = \frac{1}{2\pi(22 \text{ k}\Omega)(120 \text{ nF})} = 60.3 \text{ Hz}$$

$$Q = \frac{0.5}{2 - A_V} = \frac{0.5}{2 - 1.77} = 2.17$$

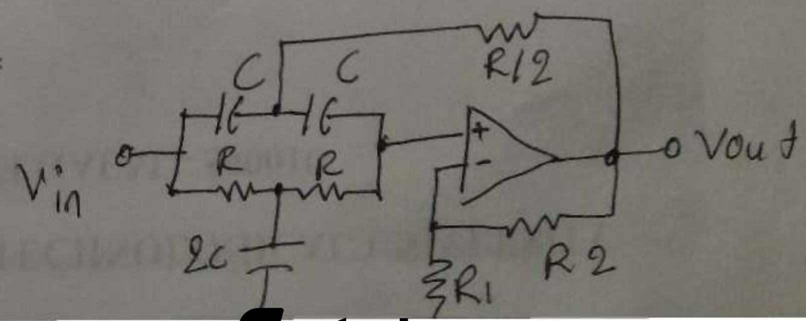


Figure 19-44 (*a*) Second-order notch filter at 60 Hz; (*b*) notch filter with $n = 20$.

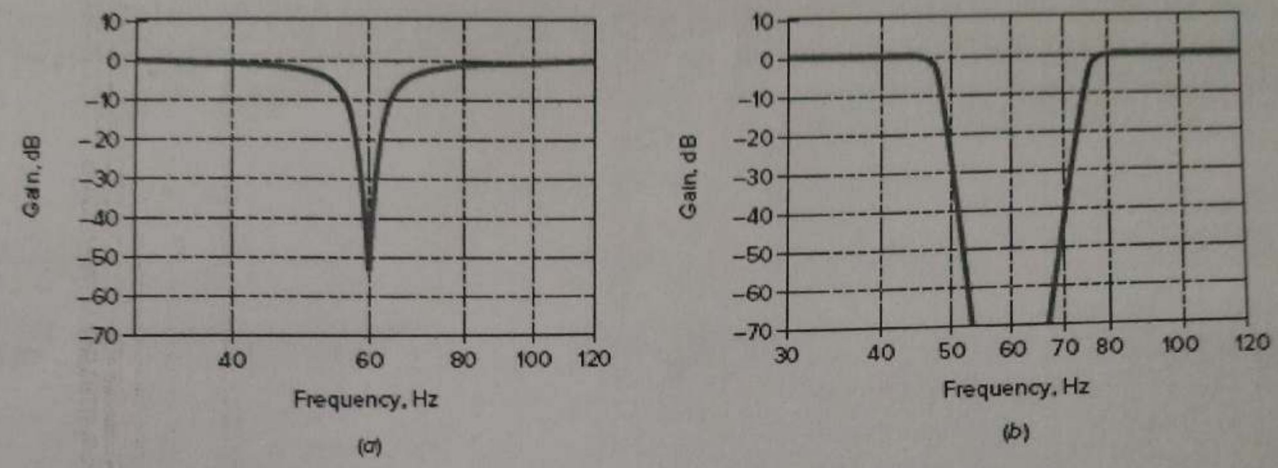


Figure 19-44*a* shows the response. Notice how sharp the notch is for a second-order filter.

By increasing the order of the filter, we can broaden the notch. For instance, Fig. 19-44*b* shows the frequency response for a notch filter with $n = 20$. The broader notch reduces component sensitivity and guarantees that the 60-Hz hum will be heavily attenuated.

PRACTICE PROBLEM 19-12 In Fig. 19-43, change R_2 to obtain a Q value of 3. Also, change the C value for a center frequency of 120 Hz.

RK