LINEAR INTEGRATED CIRCUITS (UE22EC342AB3)

- *Elective 1 course*
- *4 credit course*
- *Offered in EC and RR campus*
- *Content of Unit 4 added compared to last year syllabus*

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LINEAR INTEGRATED CIRCUITS

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Unit 1 Syllabus

Unit 1:

Development of the Ideal OpAmp Equations:

Ideal Op Amp Assumptions,
The Noninverting Op Amp,
The Inverting Op Amp,
The Adder,
The Differential Amplifier,
Complex Feedback Networks,
Video Amplifiers,
Low pass filter,
High pass filter

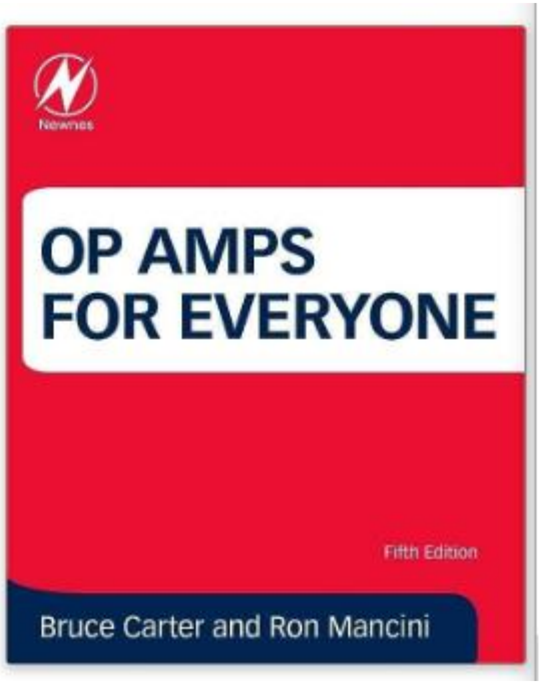
Single Supply Op Amp Design Techniques:

Single Supply versus Dual Supply
Simultaneous equations

Textbook

Textbook

- **Op Amp for everyone** Fifth edition Bruce Carter and Ron Mancini
- **Analog Filter Design**, Van Valkenburg, Oxford University Press



Unit 1 Reference book

Reference books

- Linear Integrated Design Handbook (Analog Devices)
- Operational amplifiers and linear ICs by James M Fiore 2016

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Background

- Importance of op amp
  - Op amps are first analog computer
    - Op amps are made of vacuum tubes in early years
    - Later transistor and IC came in
- Op amp types
  - μA741 μA709, M308 are popular commercial op amps
  - Some op amps are designed to work from 5Khz GBW to 5GHz GBW
  - Some op amps require power supply from 60V to 0.9V
- In many circuit analysis op amp are considered as block box
  - It performs all analog tasks
  - Many a times op amps are designed specific to application

Background

- Concept of op amp, a block that can do many things
- Op amps are always used in negative feedback configurations, rarely used in open loop configuration

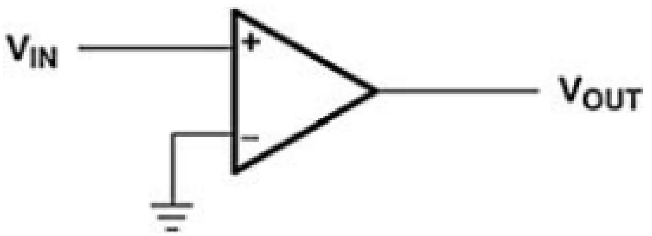

Figure 2.1
A first (and not very useful) circuit.

<u>Op amp in open loop</u>

Ideal op amp assumptions

- Ideal op amp assumes input offset is zero
- Ideal op amp assumes gain maximum at DC and minimum at high frequencies
- Input current is zero
- Op amp gain assumed to be infinity
- Voltage between input leads is zero
- Input impedance is infinite
- Output impedance is zero

Table 2.1: Basic Ideal Op Amp Assumptions

Parameter Name	Parameters Symbol	Value
Input current	I_{IN}	0
Input offset voltage	V_{OS}	0
Input impedance	Z_{IN}	∞
Output impedance	Z_{OUT}	0
Gain	a	∞

<u>Input offset voltage is defined as the difference voltage at the input to make output voltage zero</u>

Table 2.1: Basic Ideal Op Amp Assumptions

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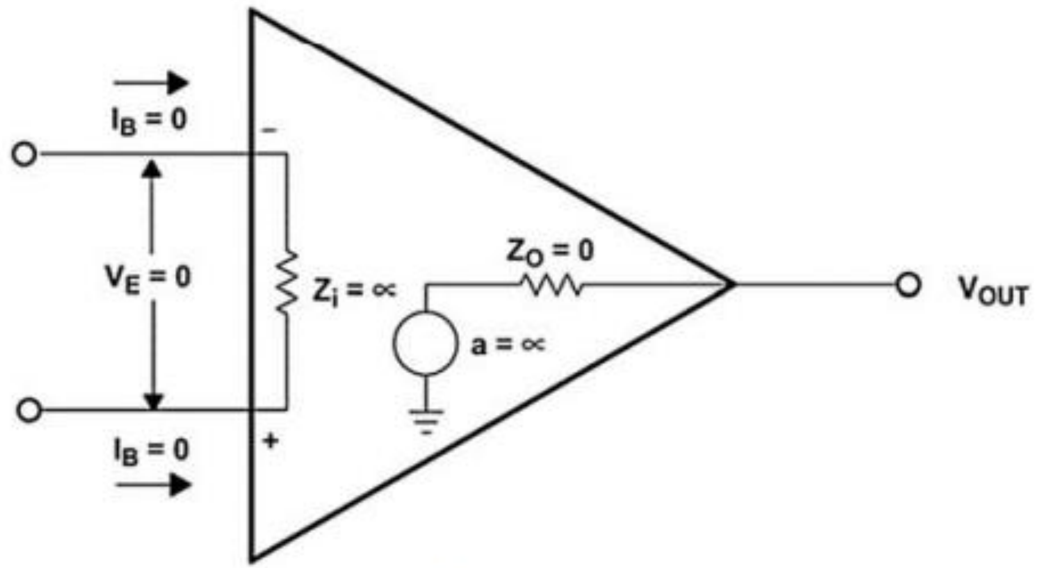
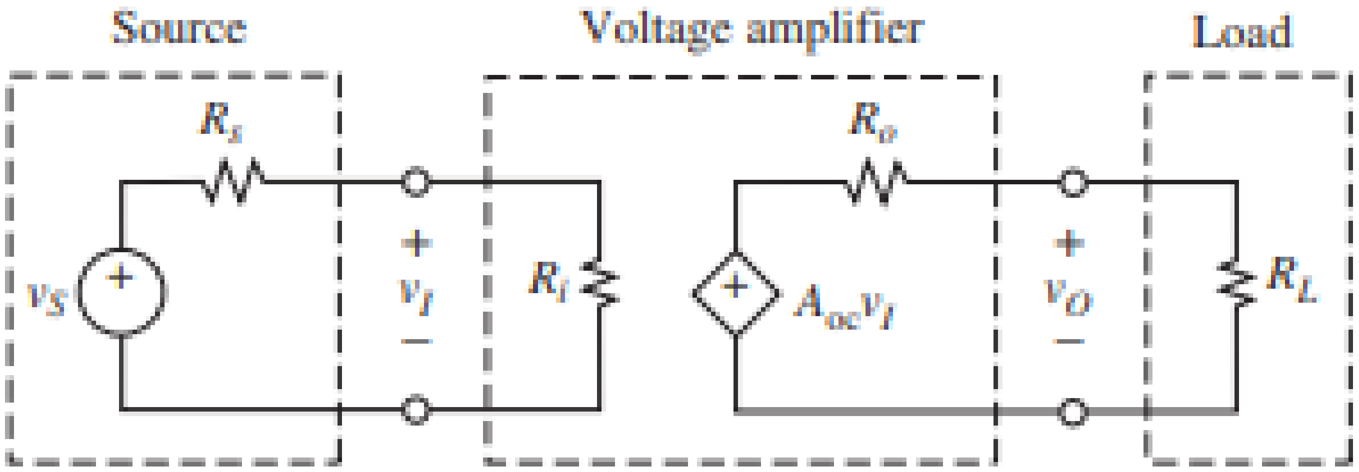


Figure 2.2
The ideal op amp.

Ideal op amp model

Unit 1 Non Ideal op amp model



$$v_O = \frac{R_L}{R_o + R_L} A_{oc} v_I \qquad v_I = \frac{R_i}{R_s + R_i} v_S \qquad \frac{v_O}{v_S} = \frac{R_i}{R_s + R_i} A_{oc} \frac{R_L}{R_o + R_L}$$

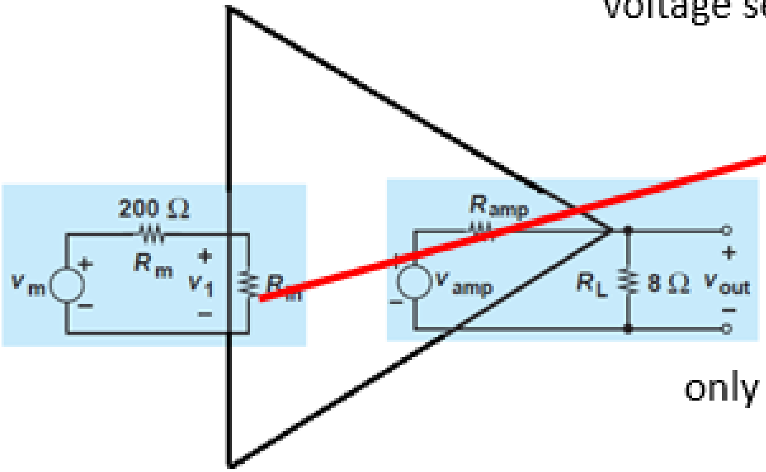
Example on finite input impedance

(a) Determine the signal level sensed by the amplifier if the circuit has an input impedance of 2 k Ω or 500Ω .

voltage sensed by the amplifier is therefore given by

$$v_1 = \frac{R_{in}}{R_{in} + R_m} v_m.$$

$R_{in} = R_i$
$R_m = R_s$



For $R_{in} = 2\ \text{k}\Omega$,

$$V1 = \frac{2000}{2200} Vm \qquad v_1 = 0.91 v_m,$$

only 9% less than the microphone signal level.

for *Rin* = 500Ω ,

$$V1 = \frac{500}{700} Vm \qquad v_1 = 0.71 v_m,$$

i.e., nearly 30% loss.

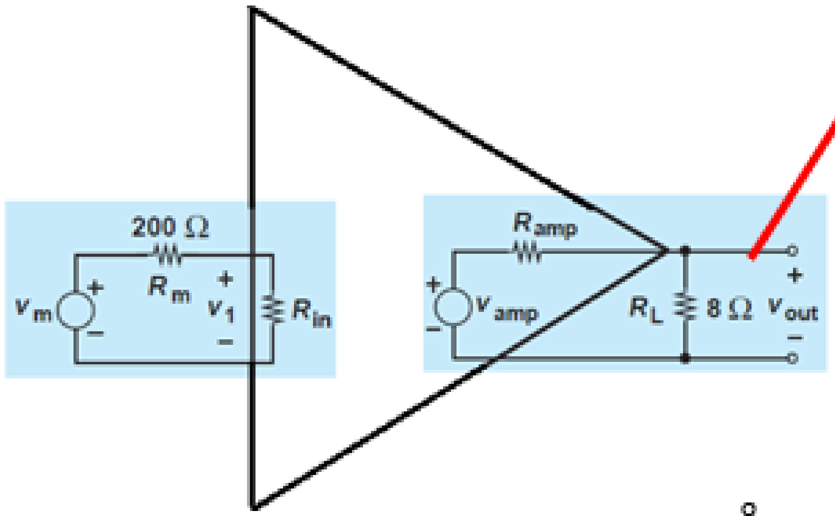
It is therefore desirable to maximize the input impedance in this case.

Example on non zero output impedance

(b) Drawing the interface between the amplifier and the speaker

$$v_{out} = \frac{R_L}{R_L + R_{amp}} v_{amp}$$

$R_{amp} = R_o$
$R_L = R_L$



$\boxed{\text{For } R_{amp} = 10\,\Omega,}$

$$\text{Vout} = \frac{8}{10+8} Vamp$$

$$v_{out} = 0.44 v_{amp},$$

$\boxed{\text{For } R_{amp} = 2\,\Omega,}$

$$\text{Vout} = \frac{8}{2+8} Vamp$$

$$v_{out} = 0.8 v_{amp}.$$

Thus, the output impedance of the amplifier must be minimized.

Unit 1 Noninverting Op amp

- Input connected to non-inverting input hence the name
- No input offset voltage
- Difference between two inputs (V_E) should be zero
- Current in R_F makes both inputs same
- Circuit diagram shown in Fig 2.3

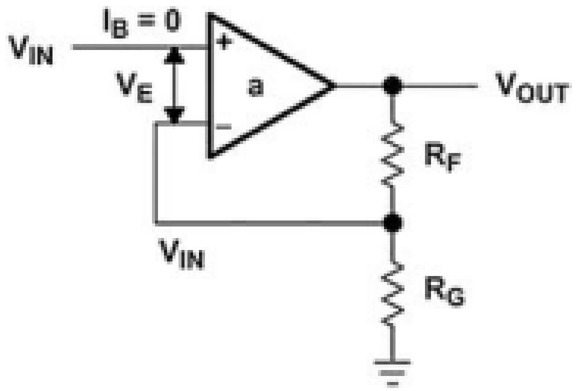


Figure 2.3

As there is no offset voltage, we take value of non inverting input and inverting input same, hence

$$V_{IN} = V_{OUT} \frac{R_G}{R_G + R_F}$$

Gain of non inverting amplifier

$$\frac{V_{OUT}}{V_{IN}} = \frac{R_G + R_F}{R_G} = 1 + \frac{R_F}{R_G}$$

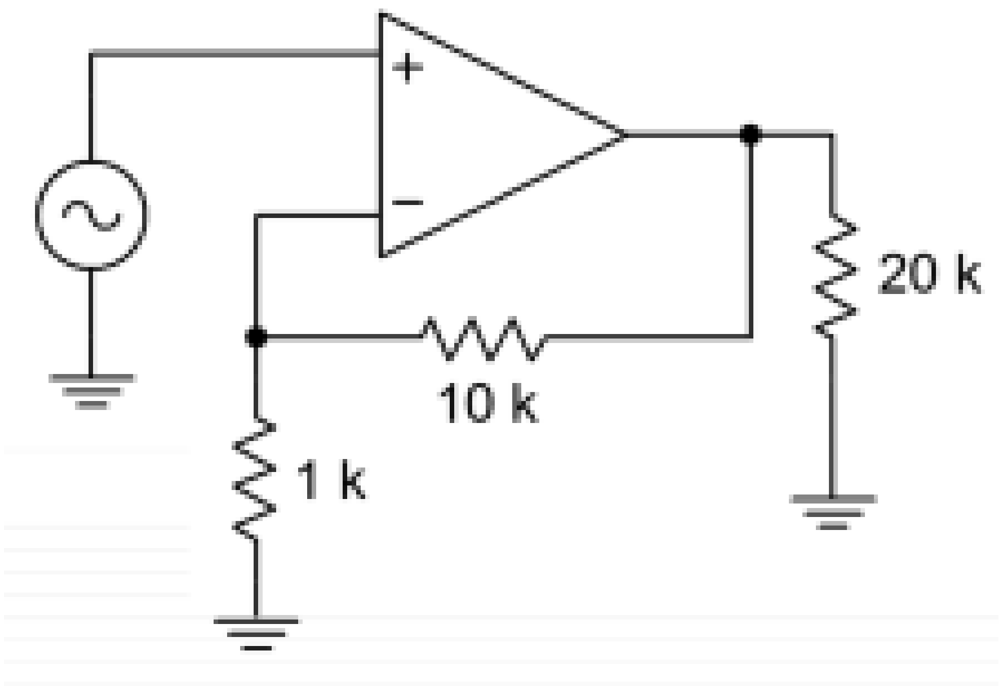
When R_G is very large,

$$\mathbf{V_{in} = V_{out}}$$

Under this condition, it works as **unity gain buffer** or **voltage follower** circuit

Note : Input offset voltage is op amp specification, V_E is external voltage condition

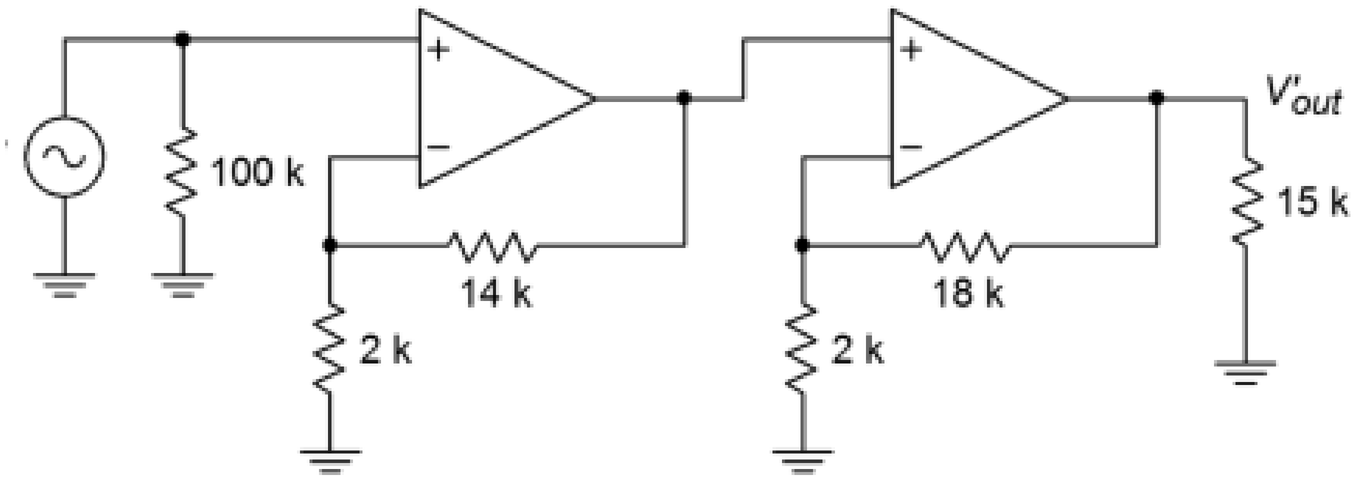
What are the input impedance and gain of the circuit in Figure



Solution

- Input impedance is infinity
- Gain is (1+ 10K/1K) = 11

What is input impedance and gain of the circuit shown in the figure?



Solution

- Input impedance is 100K
- Gain first stage is (1+14K/2K) = 8
- Gain second stage is (1+18K/2K) = 10
- Overall gain is = 8 * 10 = 80

Unit 1 Inverting Op amp

- noninverting input is grounded
- No offset voltage
- Difference between two inputs should be zero
- Current in R_F equal current flow in R_G

Using KCL,

$$I_1 = \frac{V_{IN}}{R_G} = -I_2 = -\frac{V_{OUT}}{R_F}$$

Simplifying,

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_F}{R_G}$$

Gain of inverting amplifier

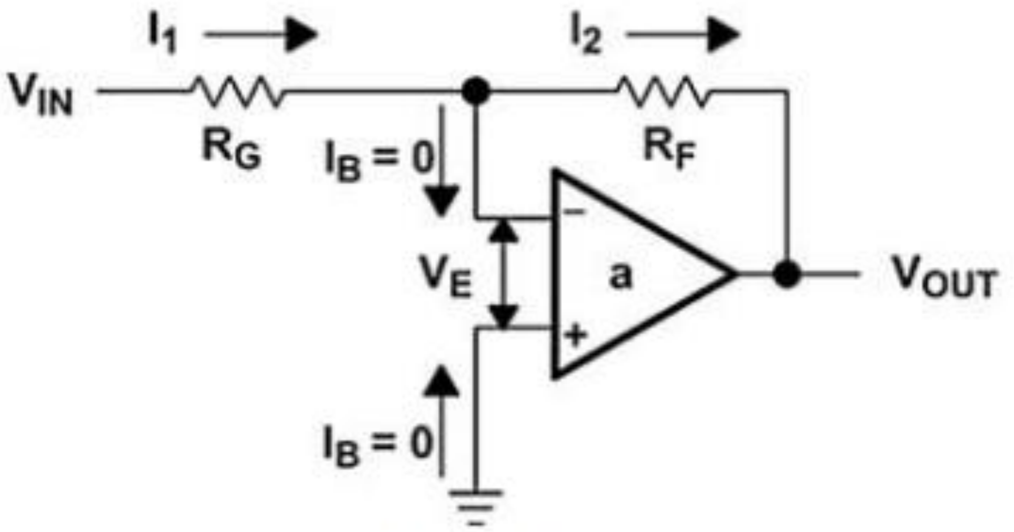
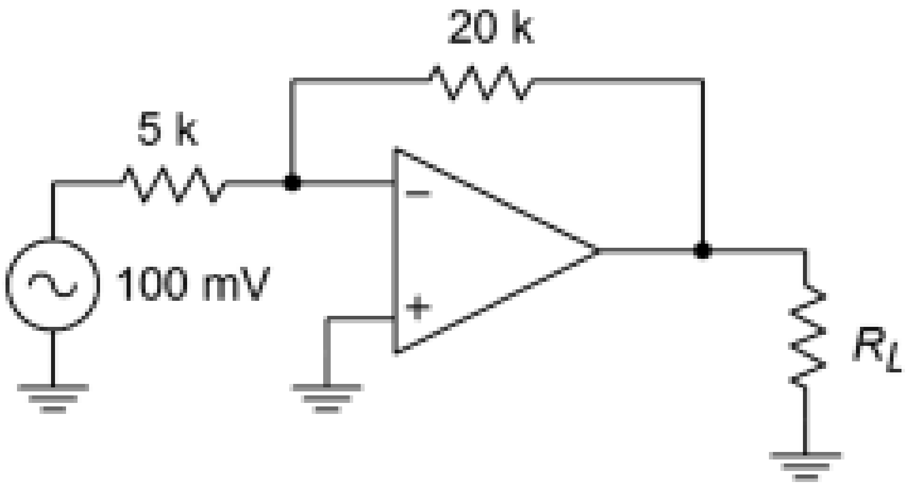


Figure 2.4

Input impedance is set by R_G

Unit 1 Inverting Op amp

What is input impedance and output voltage of the circuit shown in the figure?



Solution

- Input impedance is 5Kohm
- Output voltage is gain * input voltage
- Gain is (-20k/5k) = -4
- Output voltage is = 100mV * -4 = -400mV

Unit 1 Adder (Summing Amplifier)

- Non-inverting input is grounded
- More than one input is connected to inverting input
- Summing signals should be in inverting input terminal

To get final output, we use superposition theorem

$$V_{OUTN} = -\frac{R_F}{R_N}V_N$$

$$V_{OUT1} = -\frac{R_F}{R_1}V_1$$

$$V_{OUT2} = -\frac{R_F}{R_2}V_2$$

$$\boxed{V_{OUT} = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_N}V_N\right)}$$

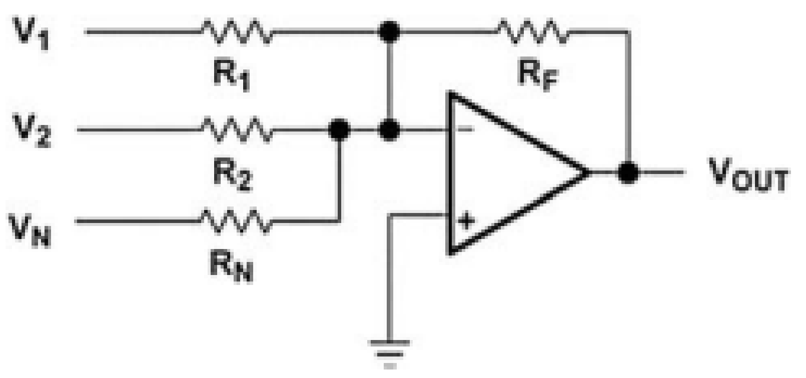


Figure 2.5

Circuit diagram

Circuit is also called summing amplifier

Design a circuit whose output is $V_{out} = -2(3V_1+4V_2+2V_3)$

Unit 1 Differential Amplifier

- Amplifies difference between two signals applied at the input
- Superposition theorem is used to calculate output

At node V_+, voltage is given by

$$V_+ = V_1 \frac{R_2}{R_1 + R_2}$$

V_+ will be taken as non inverting input

$$V_{OUT1} = V_+(G_+) = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right)$$

Taking other input, which is inverting input,

$$V_{OUT2} = V_2\left(\frac{-R_4}{R_3}\right)$$

Adding V_{OUT1} and V_{OUT2}

$$\boxed{V_{OUT} = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right) - V_2 \frac{R_4}{R_3}}$$

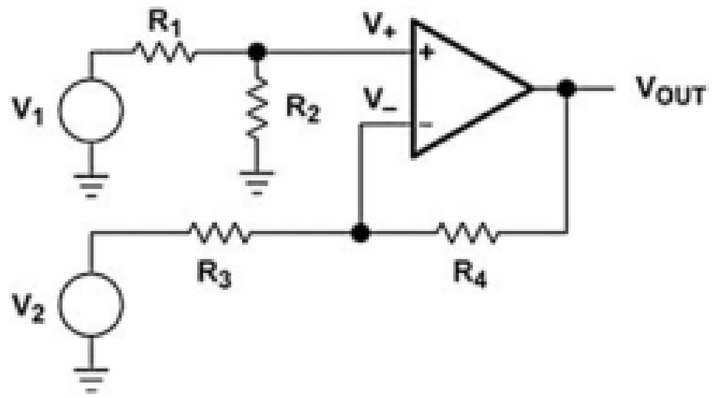


Figure 2.6

Circuit diagram

When $R_1 = R_3$ and $R_2 = R_4$

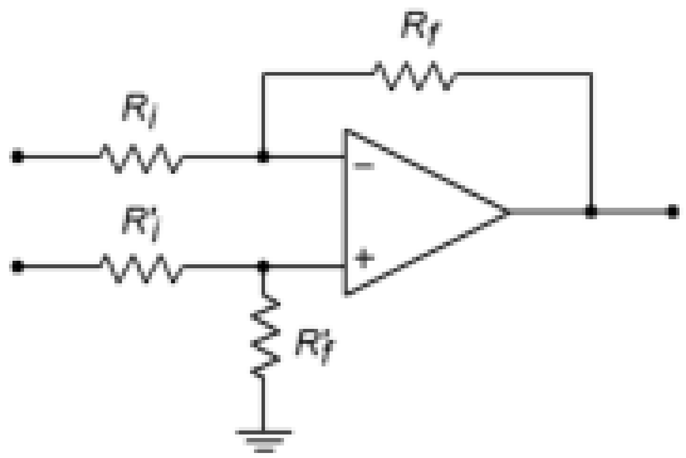
$$V_{OUT} = (V_1 - V_2)\frac{R_4}{R_3}$$

Gain of difference amplifier

Difference of voltage is amplified

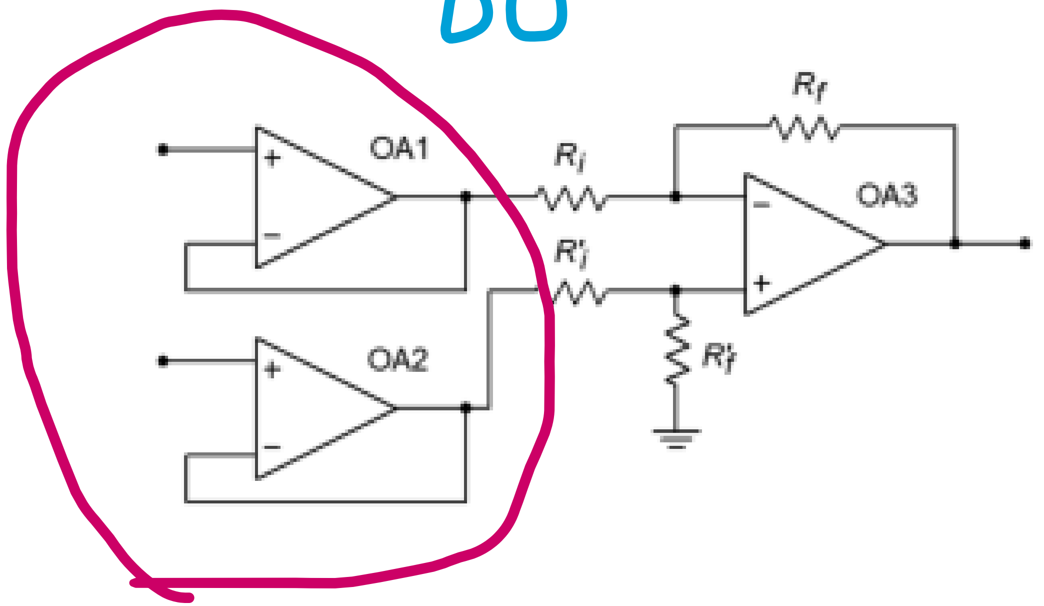
Unit 1 Instrumentation amplifier

- Specialized op amp
- Offers very high input impedance
- Derived from **differential amp**
    - Add buffer
    - Add gain
    - Merge

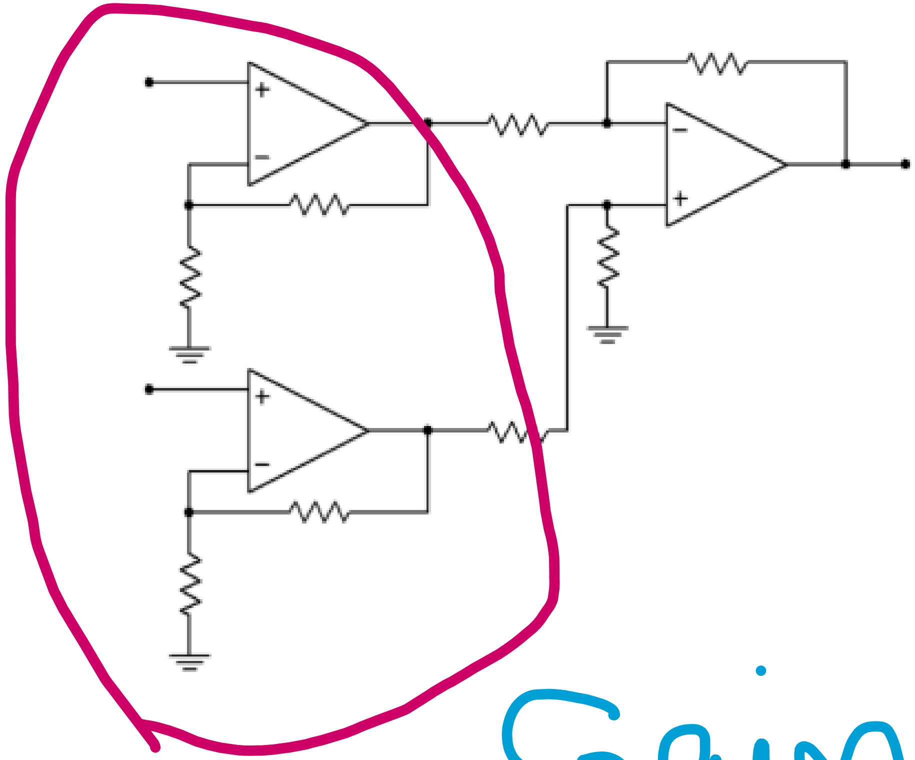


Add Buffer

Buffer



Add Gain and Merge



Gain

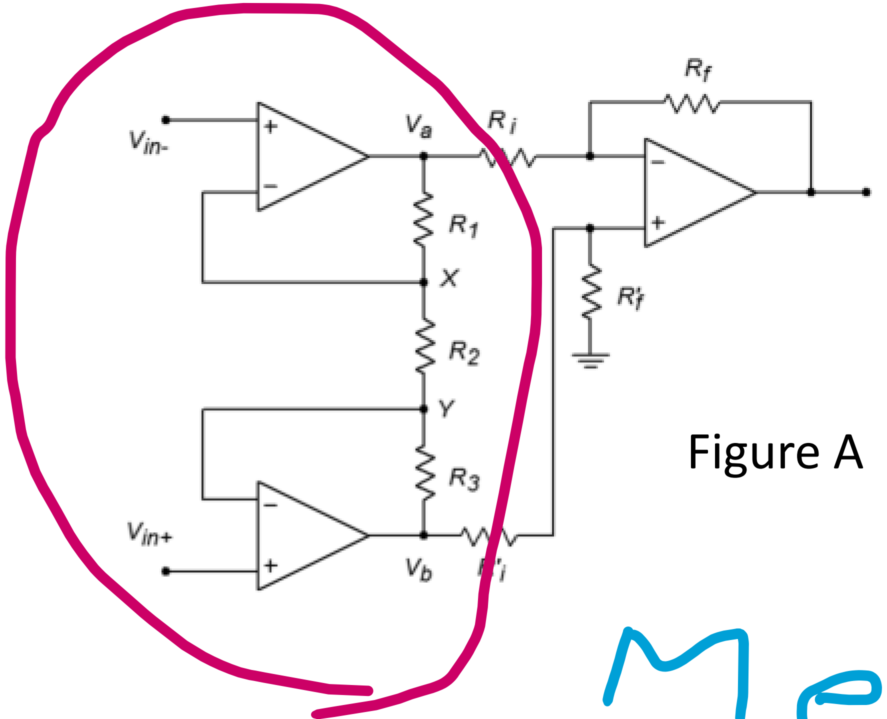


Figure A

Merge

Unit 1 Instrumentation amplifier Analysis – Derivation of gain equation

From Difference amp relation (Refer Figure A),

$$V_{out} = \frac{R_f}{R_i}(V_b - V_a)$$

From Ideal op amp relation (Both inputs at same potential),

$$V_x = V_{in-}$$

$$V_y = V_{in+}$$

The output voltage V_a must equal V_x plus the drop across R_1.

$$V_a = V_x + V_{R1}$$

Voltage drop across R_1 is given by,

$$V_{R1} = R_1 I_{R1}$$

$$V_{R1} = R_1 I_{R2}$$

Current I_{R2} is given by,

$$I_{R2} = \frac{V_x - V_y}{R_2}$$

Value of V_a is given by,

$$V_a = V_x + \frac{R_1(V_x - V_y)}{R_2}$$

After substitution,

$$V_a = V_{in-} + \frac{R_1(V_{in-} - V_{in+})}{R_2}$$

$$V_a = V_{in-} + \frac{R_1}{R_2}(V_{in-} - V_{in+})$$

$$V_a = V_{in-} + V_{in-}\frac{R_1}{R_2} - V_{in+}\frac{R_1}{R_2}$$

$$V_a = V_{in-}\left(1 + \frac{R_1}{R_2}\right) - V_{in+}\frac{R_1}{R_2}$$

By a similar derivation, the equation for V_b is found

$$V_b = V_{in+}\left(1 + \frac{R_3}{R_2}\right) - V_{in-}\frac{R_3}{R_2}$$

For gain matching R_3 is set equal to R_1. And after substitution

$$V_{out} = \frac{R_f}{R_i}\left(\left(V_{in+}\left(1 + \frac{R_1}{R_2}\right) - V_{in-}\frac{R_1}{R_2}\right) - \left(V_{in-}\left(1 + \frac{R_1}{R_2}\right) - V_{in+}\frac{R_1}{R_2}\right)\right)$$

After combining terms,

$$V_{out} = \frac{R_f}{R_i}\left((V_{in+} - V_{in-})\left(1 + \frac{R_1}{R_2}\right) + (V_{in+} - V_{in-})\frac{R_1}{R_2}\right)$$

$$\boxed{V_{out} = (V_{in+} - V_{in-})\left(\frac{R_f}{R_i}\right)\left(1 + 2\frac{R_1}{R_2}\right)}$$

Gain of instrumention amp

- T Network in feedback path, need to provide low resistance path to ground
- Use Thevenin's theorem for output voltage calculation

Disconnecting circuit at X-Y point and calculating Thevenin's equations

$$V_{TH} = V_{OUT}\frac{R_4}{R_3 + R_4}$$

$$R_{TH} = R_3 || R_4$$

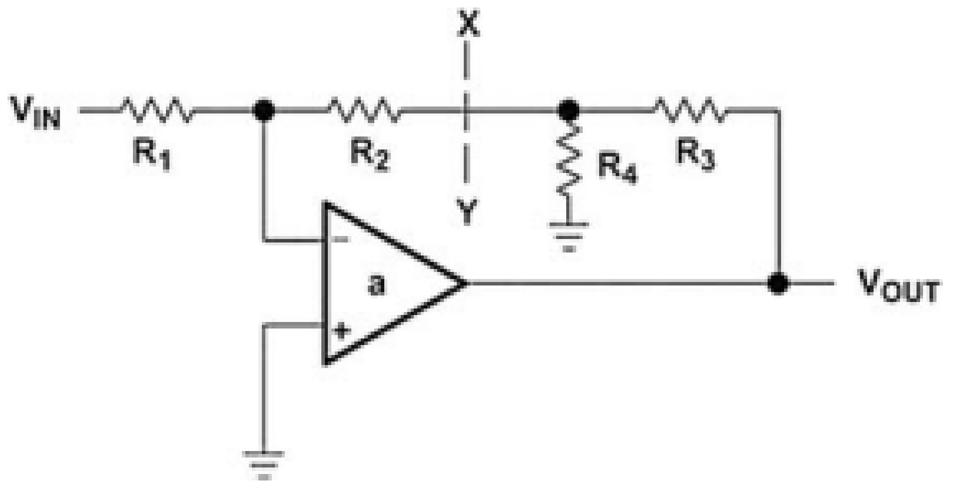


Figure 2.8

Circuit diagram

Unit 1 Complex Feedback Network

- Use Thevenin's theorem for feedback circuit calculations

Use gain equation of inverting amp

$$-\frac{V_{TH}}{V_{IN}} = \frac{R_2 + R_{TH}}{R_1}$$

Substitute R_{TH} and V_{TH} values and simplify

$$-\frac{V_{OUT}}{V_{IN}} = \frac{R_2 + R_{TH}}{R_1}\left(\frac{R_3 + R_4}{R_4}\right) = \frac{R_2 + (R_3 \| R_4)}{R_1}\left(\frac{R_3 + R_4}{R_4}\right)$$

Gain

$$-\frac{V_{OUT}}{V_{IN}} = \frac{R_2 + R_3 + \frac{R_2 R_3}{R_4}}{R_1}$$

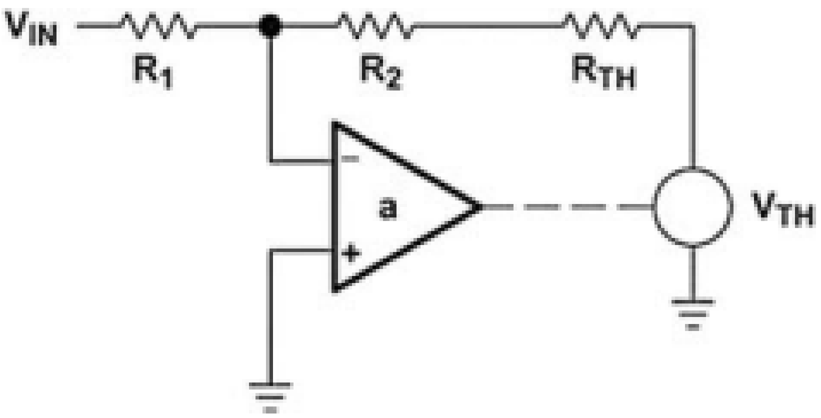


Figure 2.9

It reduces feedback resistance requirements

Unit 1 Impedance matching amplifier (Video amplifier)

- Coaxial cables used to transmit high frequency signals
- To match characteristic impedance which is 50ohm, input and output impedance should be set accordingly
- Input impedance adjusted by R_{IN} and output impedance by R_M

- R_{IN} = 50ohm
- R_M is used to adjust output impedance

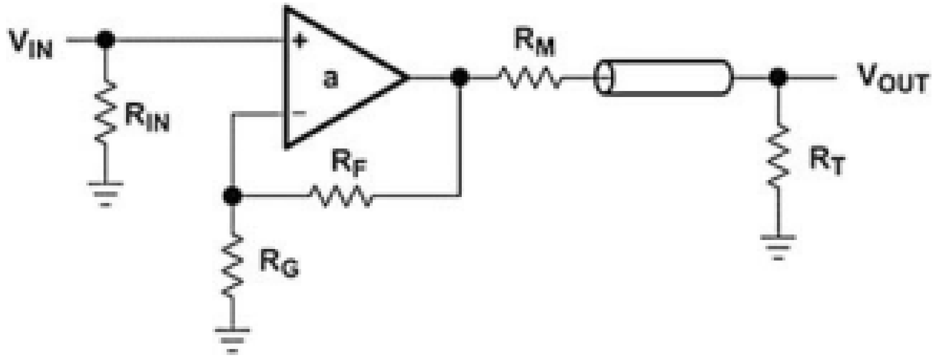


Figure 2.10

Circuit diagram

- Capacitors have impedance = $X_C = 1/2\pi fC$ where f is frequency, C capacitance value
- Break frequency (Cut off frequency) occurs at $f = 1/2\pi RC$ where gain is reduced to -3db from original value
- At low frequency, R_F dominates and at high frequency C_F dominates

Gain

$$\frac{V_{OUT}}{V_{IN}} = -\frac{X_C \| R_F}{R_G}$$

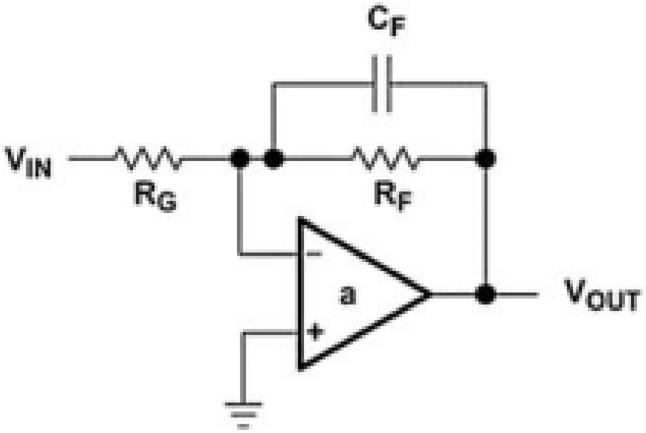


Figure 2.11
Low-pass filter.

Circuit is also referred as integrator

- Capacitors have impedance = $X_C = 1/2\pi fC$
- Break frequency occurs at $f = 1/2\pi RC$ where is gain is reduced to -3db
- At low frequency, R_G dominates and at high frequency C_F dominates

$$\frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_F}{X_C \| R_G}$$

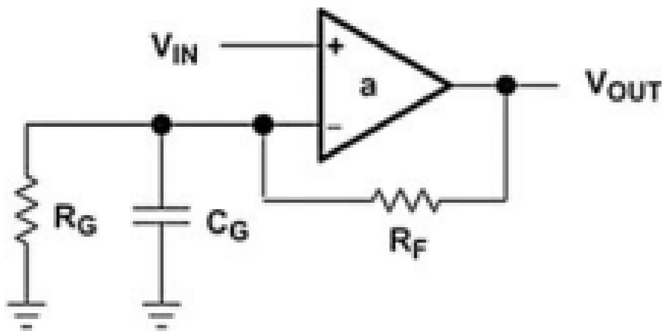


Figure 2.12
High-pass filter.

Importance of single supply op amps

- Dual power supply always takes mid point reference as ground, This is not useful for battery operated devices
- Concept of virtual ground is built around signal swing from positive to negative taking virtual ground as mid point
- Create localised ground, so called DC operating point

- Circuit of DC operating points are isolated using capacitors

- Use direct voltage

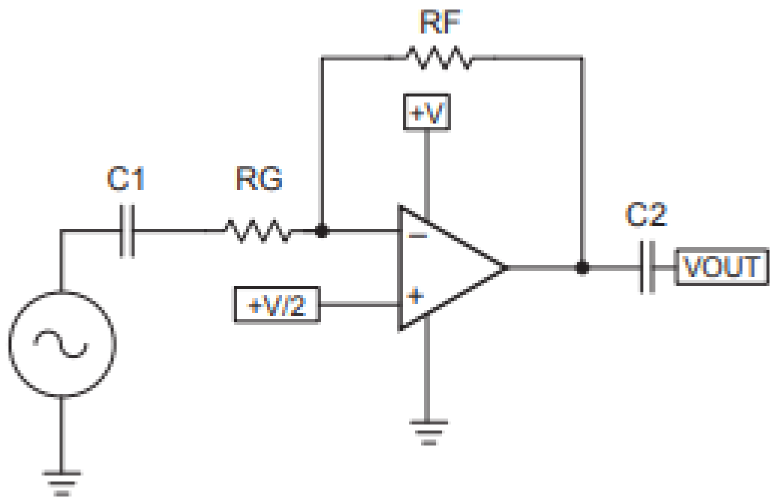


Figure 3.2

- For AC signal, it acts as inverting amplifier
- For DC signal, it acts as non inverting amplifier with unity gain
- For DC signal, Positive input, negative input and output are at DC potential

Note : DC operating point need not be always V/2, where V is positive supply

Unit 1 Single supply op amp design techniques 2

- Use voltage divider circuit

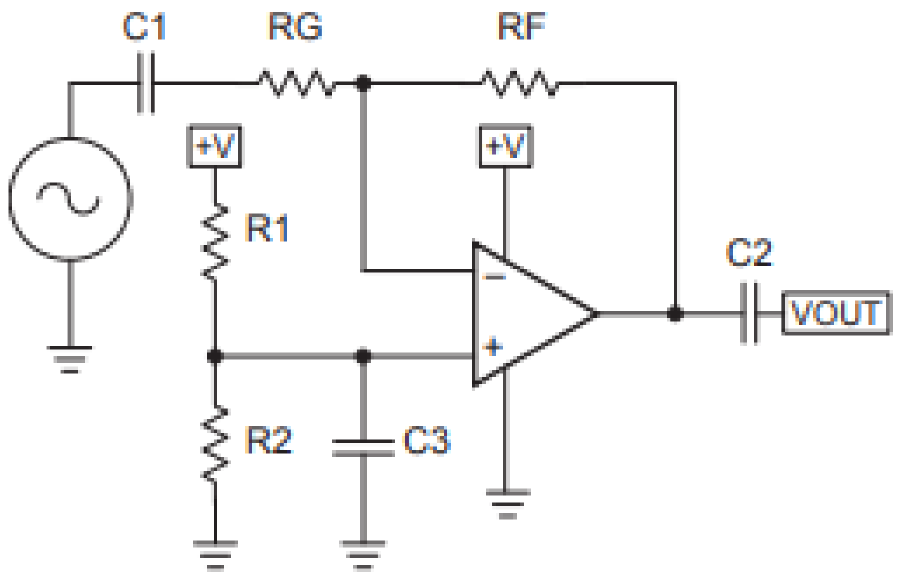


Figure 3.3

- Voltage divider circuit can be used to generate mid point voltage value to set DC operating point
- Resistor value has to be larger to reduce power consumption
- Capacitor C3 used to supress noise

- **Use voltage reference circuit**

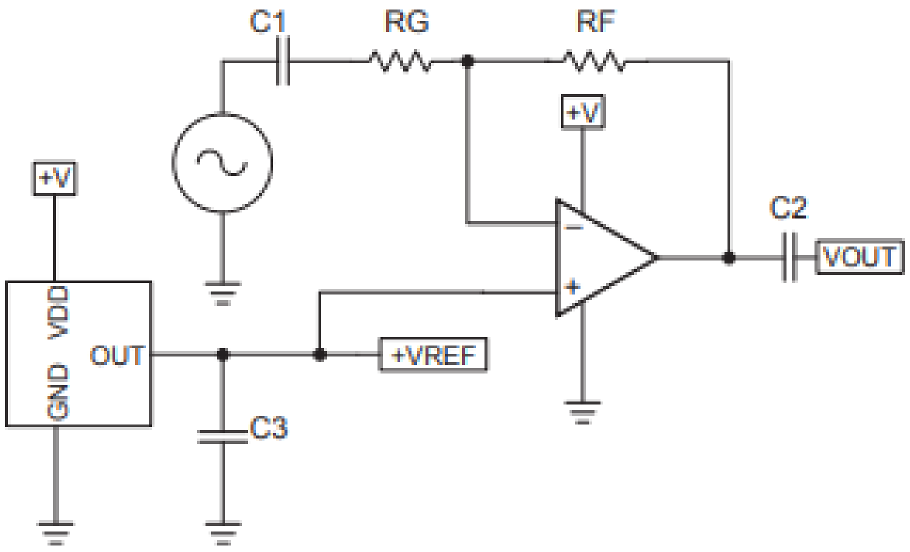


Figure 3.4

- Voltage reference circuit or IC can be used to produce reference voltage instead of resistor divider circuit

Unit 1 Single supply op amp design techniques 4

- Use reference voltage of other circuit

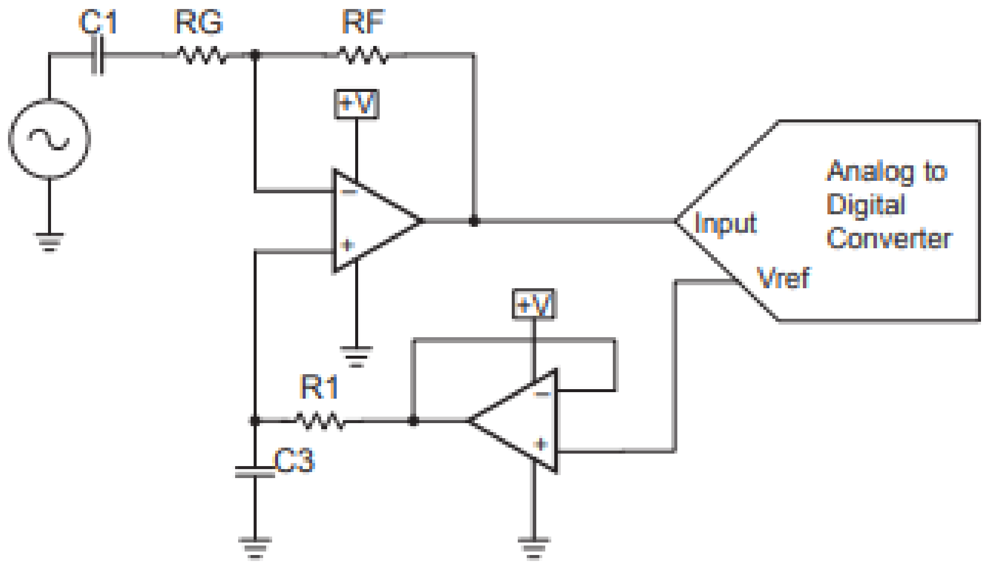


Figure 3.6
Correct voltage reference buffering.

- Reference can be taken from other circuits like ADC reference
- C1 and C3 selected based on signal frequency
- R1 is used for isolation of op amp used for buffer

Unit 1 Issues with Non inverting stage in single supply mode

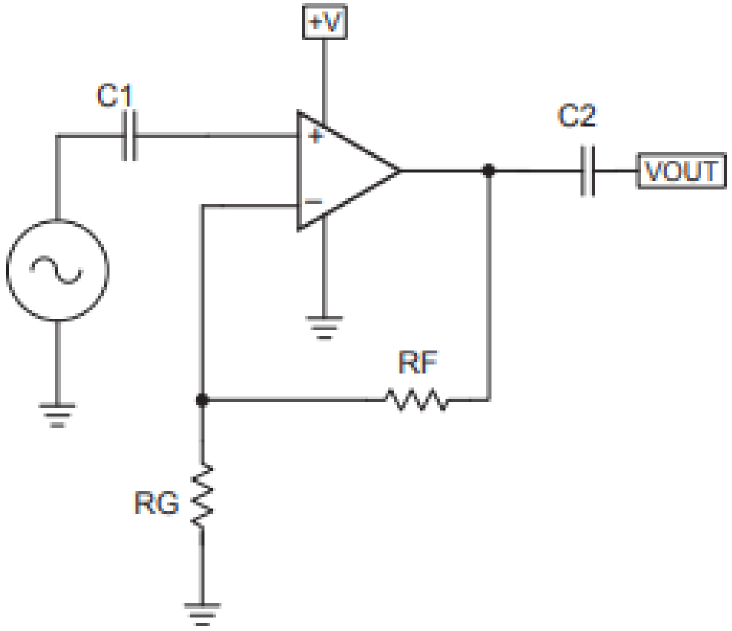


Figure 3.7
Incorrect noninverting single-supply stage.

- For DC, Non inverting terminal is floating !
- Circuit can not define operating point

Unit 1 Issues with Non inverting stage in single supply mode

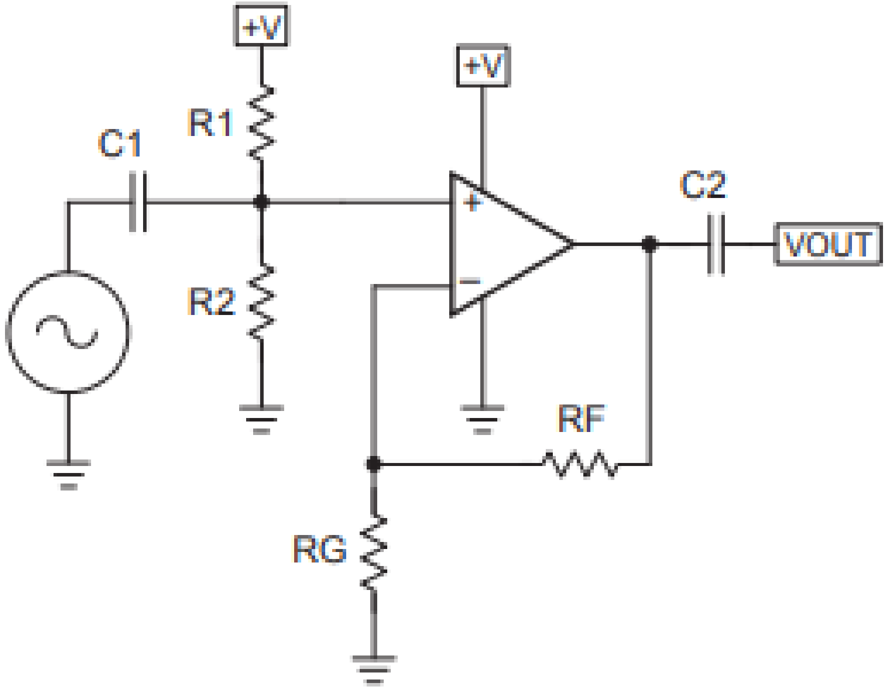
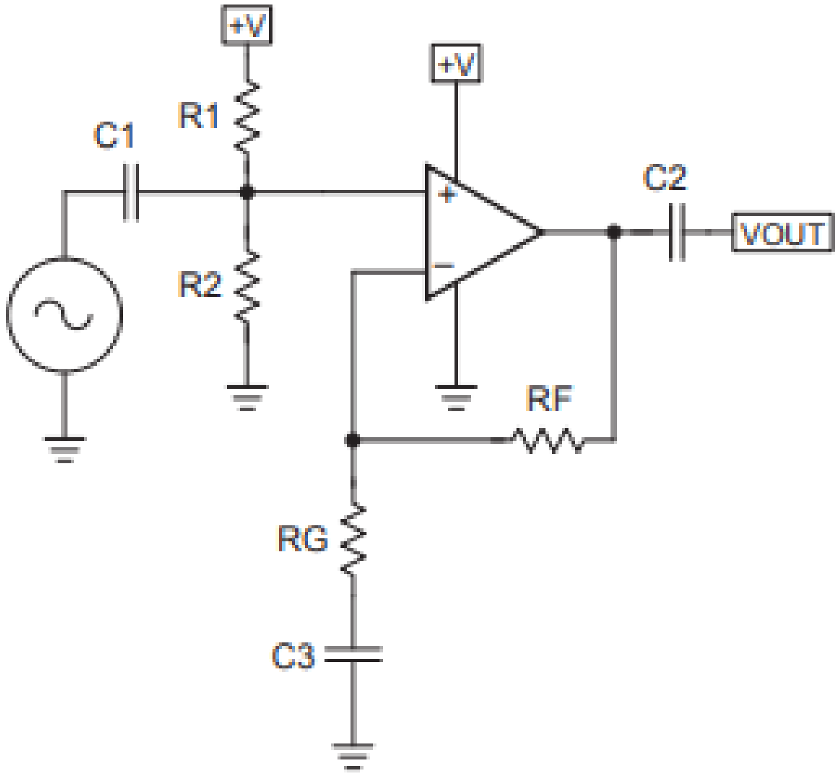


Figure 3.8
Another incorrect noninverting single-supply stage.

- We can define inverting input using R1 and R2 for DC
- For output voltage equal to V, DC is defined. However for output voltage equal to 0, DC is not defined !

Unit 1 Non inverting stage in single supply mode



- A capacitor C3 is added which does not allow DC to flow
- For DC, gain is unity
- and for AC gain is $1+R_F/R_G$

Unit 1 DC Coupled Single supply op amp design techniques

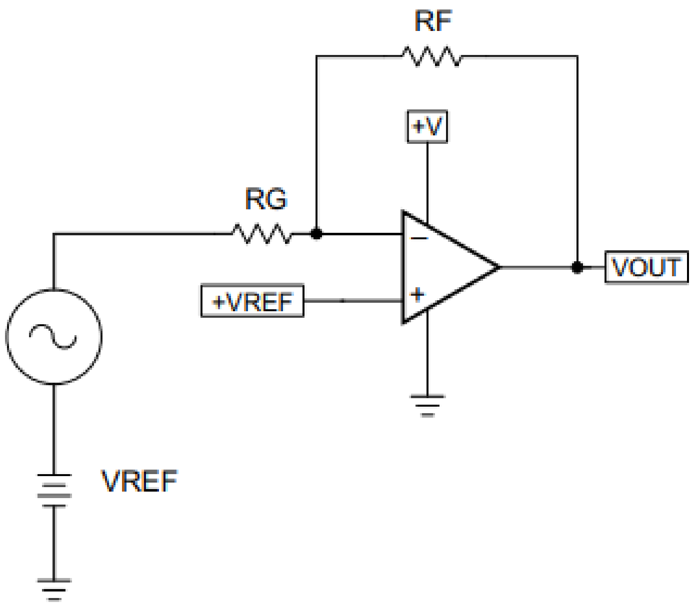


Figure 4.1
A simple transducer interface example.

- In this type, DC signal is coupled with AC signal
- Need to preserve DC level for applications like transducers
- If positive supply is 10V, output voltage range is from 0 to 10V
- Output should support both positive and negative inputs, along with DC level

Any difference in DC levels of two inputs, lead to offset

Unit 1 DC Coupled Single supply op amp design techniques

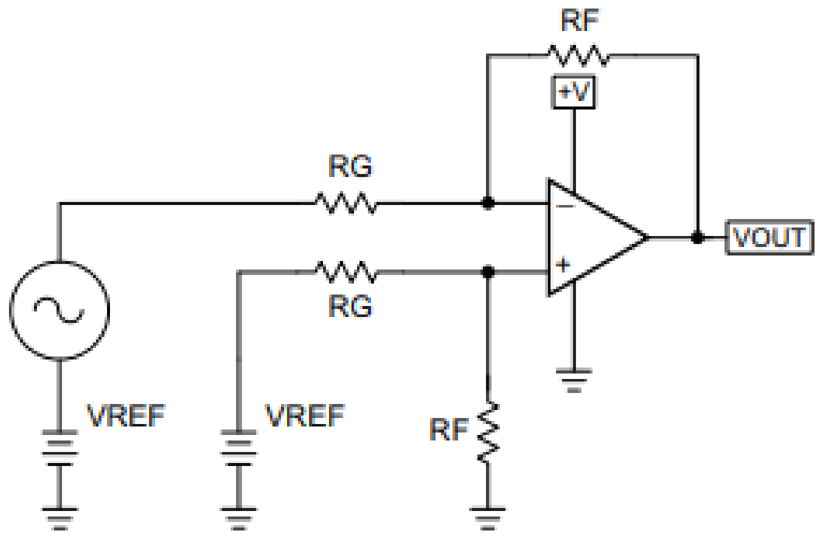


Figure 4.2
Split-supply op amp circuit with common-mode voltage.

- Input bias voltage is used instead of a reference
- Use same RG and RF for both terminals. This avoids variations in the voltage due to resistance value variations

- **VREF can be considered as common mode voltage**
- **DC operating point is VREF/2**

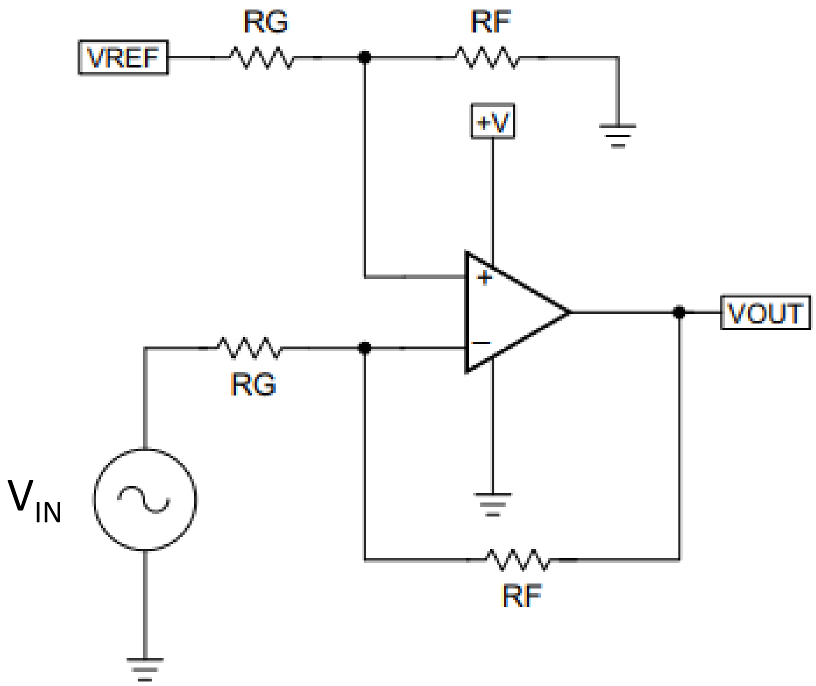


Figure 4.3
Inverting op amp with DC offset.

Inverting

- Here, AC and DC given separately, one to inverting and other to non inverting.
- Reference is set by divider circuit
- AC Gain by resistors connected to inverting terminal

Using relations from difference amplifier,

$$V_{OUT} = V_{REF}\left(\frac{R_F}{R_G + R_F}\right)\left(\frac{R_F + R_G}{R_G}\right) - V_{IN}\frac{R_F}{R_G}$$

$$V_{OUT} = (V_{REF} - V_{IN})\frac{R_F}{R_G}$$

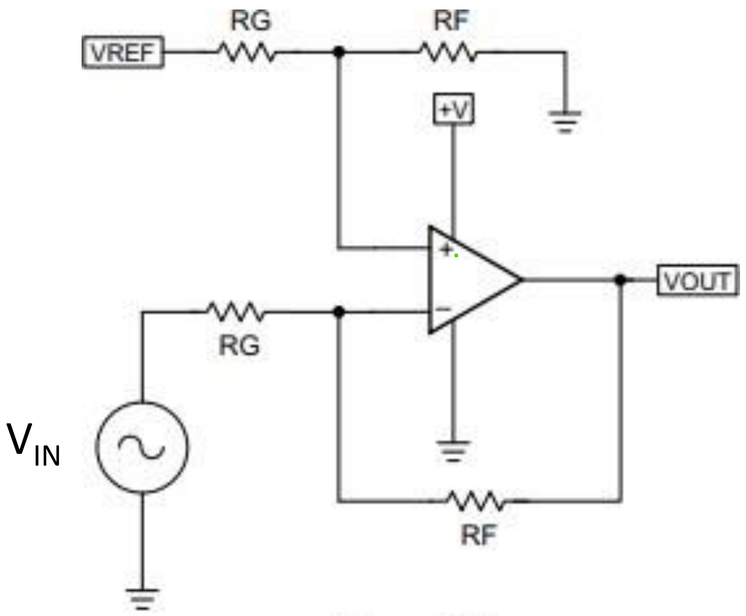


Figure 4.3
Inverting op amp with DC offset.

Inverting

When $V_{REF} = V_{IN}$,

$$V_{OUT} = (V_{REF} - V_{IN})\frac{R_F}{R_G} = (V_{IN} - V_{IN})\frac{R_F}{R_G} = 0$$

When $V_{REF} = 0$,

$$V_{OUT} = -V_{IN}(R_F/R_G).$$

When $V_{REF} = 0$, and V_{IN} is positive

$$V_{IN} \geq 0, \quad V_{OUT} = 0$$

When $V_{REF} = 0$, and V_{IN} is negative

$$V_{IN} \leq 0, \quad V_{OUT} = |V_{IN}|\frac{R_F}{R_G}$$

Unit 1 DC coupled Single supply op amp design analysis- Inverting

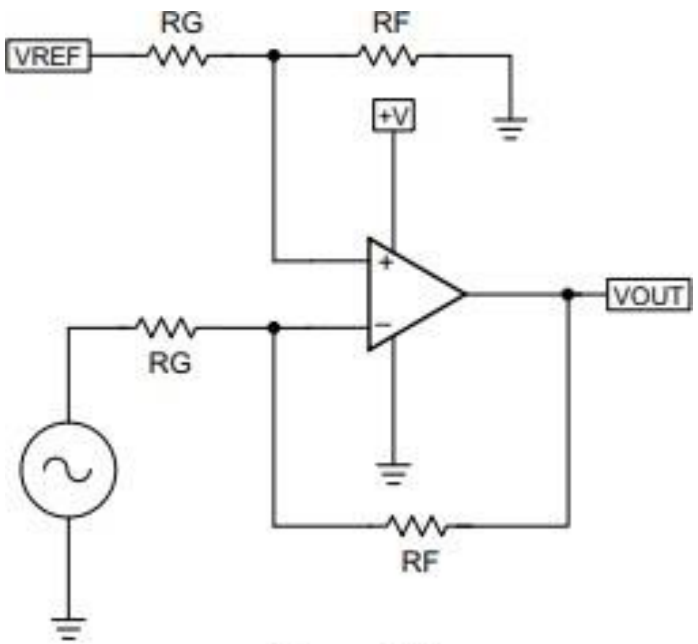


Figure 4.3
Inverting op amp with DC offset.

Inverting

When $V_{REF} = V_{CC}$, the supply voltage

$$V_{OUT} = (V_{CC} - V_{IN})\frac{R_F}{R_G}$$

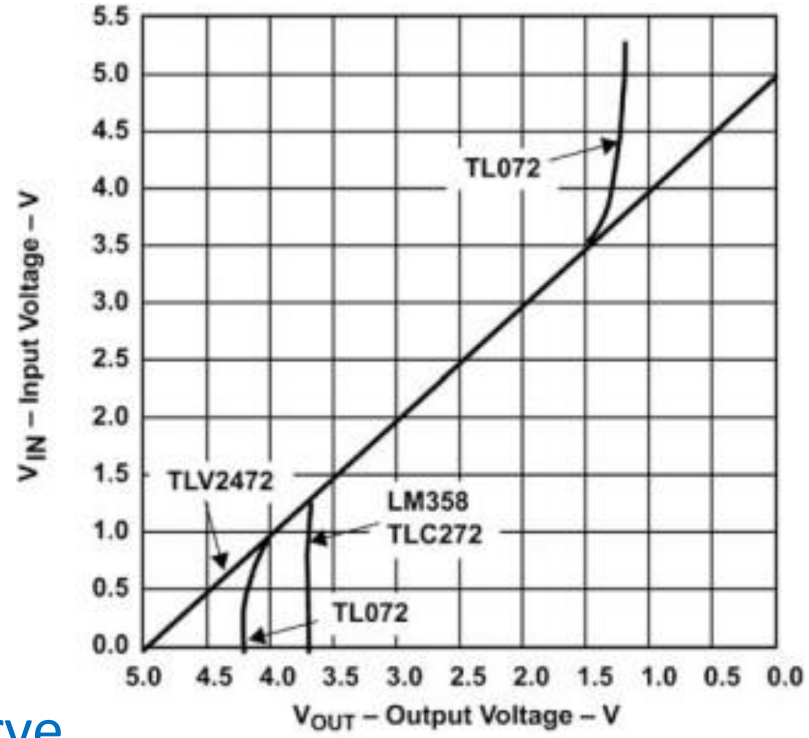


Figure 4.5

Transfer Curve

V_{CC} = 5V,
V_{IN} is varied from 0 to 5V

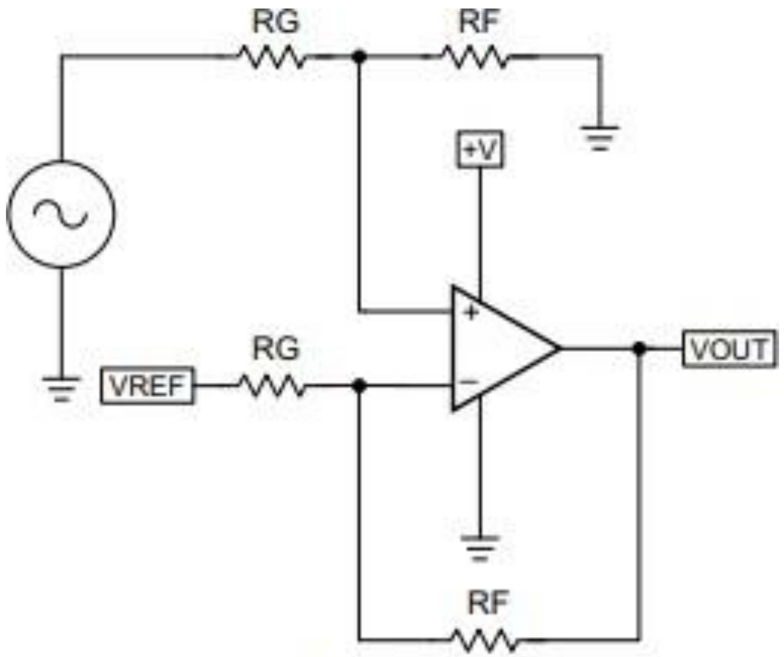


Figure 4.6

Non Inverting

- AC and DC inputs separately given.
- AC Gain by resistors connected to non inverting terminal

Using relations from difference amplifier,

$$V_{OUT} = V_{IN}\left(\frac{R_F}{R_G + R_F}\right)\left(\frac{R_F + R_G}{R_G}\right) - V_{REF}\frac{R_F}{R_G}$$

$$V_{OUT} = (V_{IN} - V_{REF})\frac{R_F}{R_G}$$

Unit 2 DC coupled Single supply op amp design analysis – Non inverting

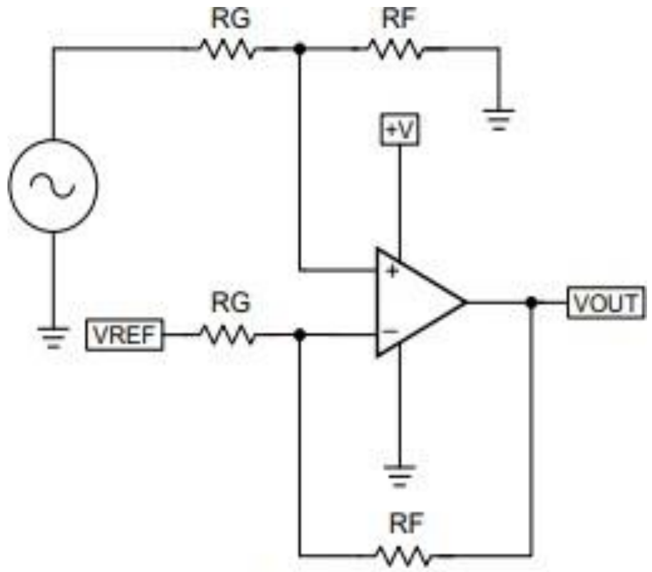


Figure 4.6

When $V_{REF} = V_{IN}$,

$$V_{OUT} = (V_{REF} - V_{IN})\frac{R_F}{R_G} = (V_{IN} - V_{IN})\frac{R_F}{R_G} = 0$$

When $V_{REF} = 0$,

$$V_{OUT} = V_{IN}\frac{R_F}{R_G},$$

When $V_{REF} = 0$, and V_{IN} is positive

$$V_{IN} \geq 0, \quad V_{OUT} = V_{IN}$$

When $V_{REF} = 0$, and V_{IN} is negative

$$V_{IN} \leq 0, \quad V_{OUT} = 0$$

Non Inverting

Unit 1 DC coupled Single supply op amp design analysis – Non inverting

When V_{CC} = 5V and R_F = R_G = 100Kohm

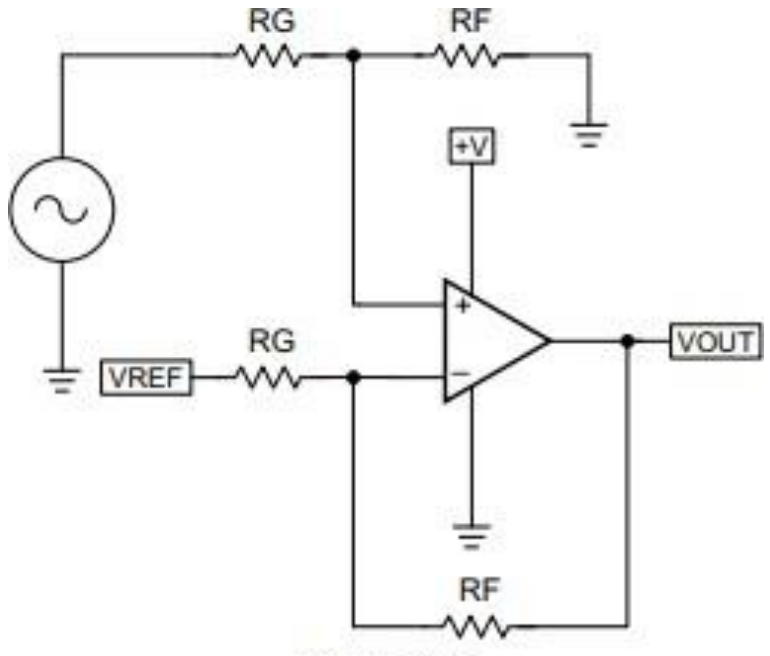


Figure 4.6

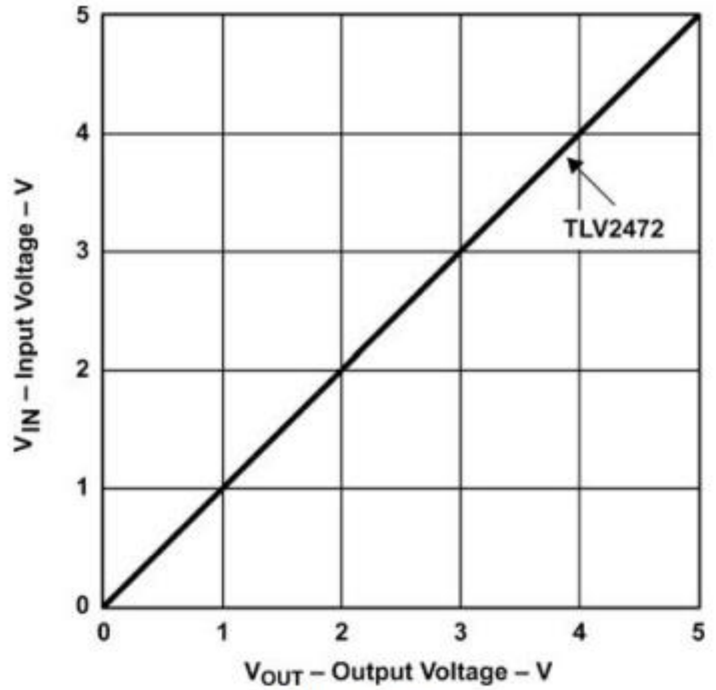


Figure 4.7
Transfer curve for noninverting op amp.

Non Inverting

Transfer Curve

- Linear op amp transfer function is limited to equation of straight line $\underline{y = +/-mx+/-b}$
- Here **m** is gain, **b** is offset, **x** is input and **y** is output
- Four possible cases based on **m** and **b**

$$V_{OUT} = +mV_{IN} + b$$
$$V_{OUT} = +mV_{IN} - b$$
$$V_{OUT} = -mV_{IN} + b$$
$$V_{OUT} = -mV_{IN} - b$$

Circuit Requirement

A sensor output signal ranging from 0.1V to 0.2V must be interfaced with analog to digital converter that has an input range of 1V to 4V

From requirement,

1. $V_{OUT} = 1\ V$ at $V_{IN} = 0.1\ V$
2. $V_{OUT} = 4\ V$ at $V_{IN} = 0.2\ V$

Unit 1 Simultaneous equations An example

After inserting data points,

V_o V_{in}

$$1 = m(0.1) + b$$
$$4 = m(0.2) + b$$

Solving for **b**, $\mathbf{b = -2}$

Solving for **m**, $\mathbf{m = 30}$

Final equation is, $V_{OUT} = 30V_{IN} - 2$

Gain is 30
Offset is -2

Unit 1 Simultaneous equations in form y = mx+b (case 1)

- Both input and reference connected to non inverting input
- Both m and b are positive

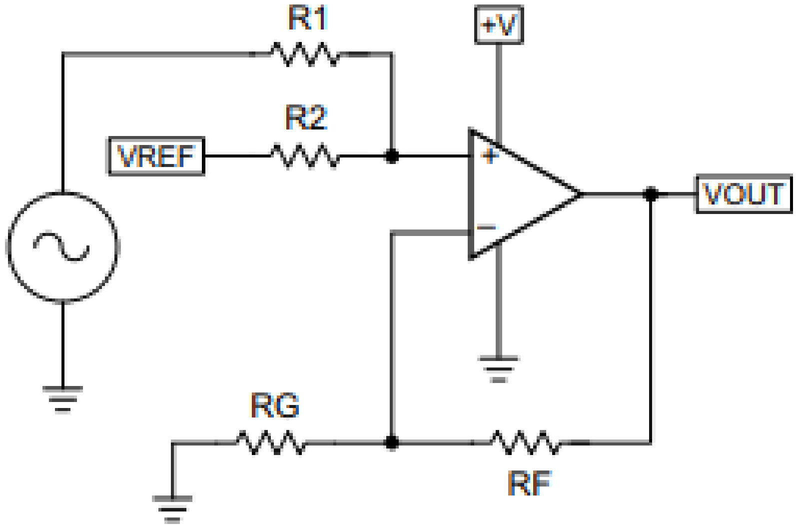


Figure 4.8
Schematic for Case 1: $V_{OUT} = +mV_{IN} + b$.

$$V_{OUT} = V_{IN}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_F + R_G}{R_G}\right) + V_{REF}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_F + R_G}{R_G}\right)$$

Compare with $V_{OUT} = +mV_{IN} + b$

Equating coefficients yields

$$m = \left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_F + R_G}{R_G}\right)$$

$$b = V_{REF}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_F + R_G}{R_G}\right)$$

As both m and b are positive, both of them connected to non inverting input

Unit 1 Case 1 example

Circuit has following specifications

$V_{OUT} = 1V$ at $V_{IN} = 0.01V$
$V_{OUT} = 4.5V$ at $V_{IN} = 1V$

The data are substituted into simultaneous equations.

$$1 = m(0.01) + b$$
$$4.5 = m(1.0) + b$$

$$100 = m(1.0) + 100b$$
$$b = \frac{95.5}{99} = 0.9646$$

$$m = \frac{1-b}{0.01} = \frac{1-0.9646}{0.01} = 3.535$$

$$\frac{R_F + R_G}{R_G} = m\left(\frac{R_1 + R_2}{R_2}\right) = \frac{b}{V_{CC}}\left(\frac{R_1 + R_2}{R_1}\right)$$

$$R_2 = \frac{3.535}{\frac{0.9646}{5}} R_1 = 18.316 R_1$$

Choose $R_1 = 10\ \text{k}\Omega$, and that sets the value of $R_2 = 183.16\ \text{k}\Omega$.

Unit 1 Case 1 example (continued)

Circuit has following specifications

$V_{OUT} = 1V$ at $V_{IN} = 0.01V$
$V_{OUT} = 4.5V$ at $V_{IN} = 1V$

$$\frac{R_F + R_G}{R_G} = m\left(\frac{R_1 + R_2}{R_2}\right) = 3.535\left(\frac{180 + 10}{180}\right) = 3.73$$

$$R_F = 2.73R_G$$

The resulting circuit equation is given below.

$$V_{OUT} = 3.5V_{IN} + 0.97$$

The gain setting resistor, R_G, is selected as 10 kΩ, and 27 kΩ,

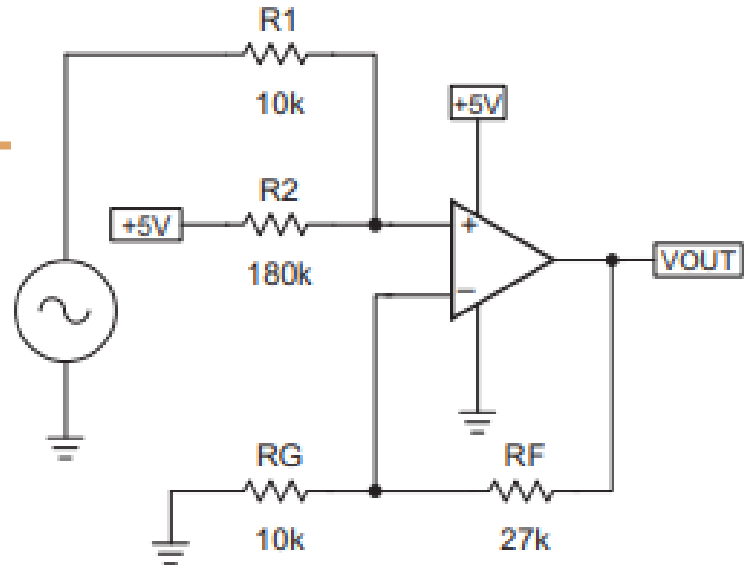


Figure 4.9

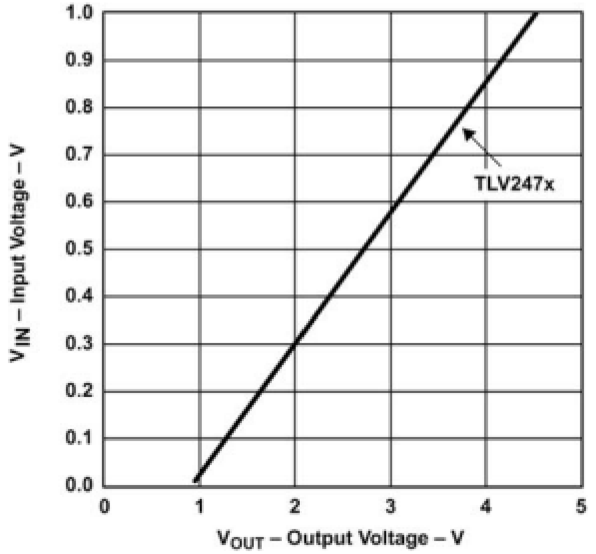


Figure 4.10
Case 1 example circuit measured transfer curve.

Unit 1 Case 2 y = mx-b

- Input connected to non inverting input and reference connected to inverting

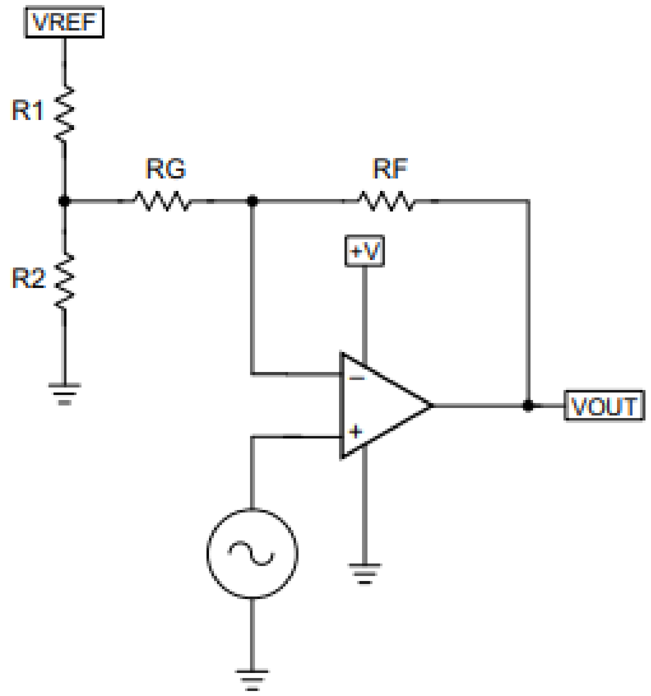


Figure 4.11
Schematic for Case 2: $V_{OUT} = +mV_{IN} - b$.

$$V_{OUT} = V_{IN}\left(\frac{R_F + R_G + R_1 \| R_2}{R_G + R_1 \| R_2}\right) - V_{REF}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_F}{R_G + R_1 \| R_2}\right)$$

$$m = \frac{R_F + R_G + R_1 \| R_2}{R_G + R_1 \| R_2}$$

$$|b| = V_{REF}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_F}{R_G + R_1 \| R_2}\right)$$

As m is positive and b are negative, m connected to non inverting and b to inverting

Unit 1 Case 2 example

Circuit has following specifications

$V_{OUT} = 1.5V$ at $V_{IN} = 0.2V$
$V_{OUT} = 4.5V$ at $V_{IN} = 0.5V$

Simultaneous equations

$$1.5 = 0.2m + b$$
$$4.5 = 0.5m + b$$

From these equations we find that $b = -0.5$ and $m = 10$.

$R_1 \| R_2 << R_G$ simplifies the calculations of the resistor values.

$$m = 10 = \frac{R_F + R_G}{R_G}$$
$$R_F = 9R_G$$

Let $R_G = 20\ k\Omega$, and then $R_F = 180\ k\Omega$.

$$b = V_{CC}\left(\frac{R_F}{R_G}\right)\left(\frac{R_2}{R_1 + R_2}\right) = 5\left(\frac{180}{20}\right)\left(\frac{R_2}{R_1 + R_2}\right)$$
$$R_1 = \frac{1 - 0.01111}{0.01111} R_2 = 89R_2$$

Select $R_2 = 820\ \Omega$, and R_1 equals $72.98\ k\Omega$.

Unit 1 Case 2 example (continued)

Circuit has following specifications

$V_{OUT} = 1.5V$ at $V_{IN} = 0.2V$
$V_{OUT} = 4.5V$ at $V_{IN} = 0.5V$

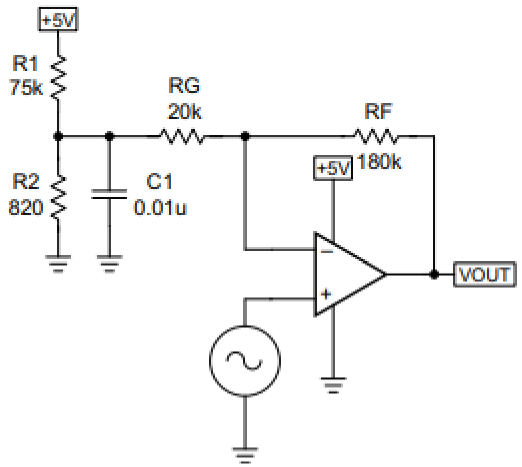


Figure 4.12
Case 2 example circuit.

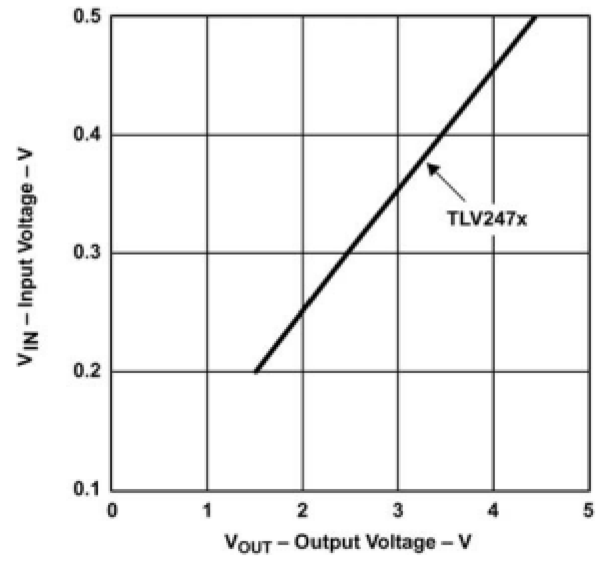


Figure 4.13
Case 2 example circuit measured transfer curve.

Unit 1 Case 3 y = -mx+b

Input connected to inverting input and reference connected to non inverting

$$V_{OUT} = -V_{IN}\left(\frac{R_F}{R_G}\right) + V_{REF}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_F + R_G}{R_G}\right)$$

$$|m| = \frac{R_F}{R_G}$$

$$b = V_{REF}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_F + R_G}{R_G}\right)$$

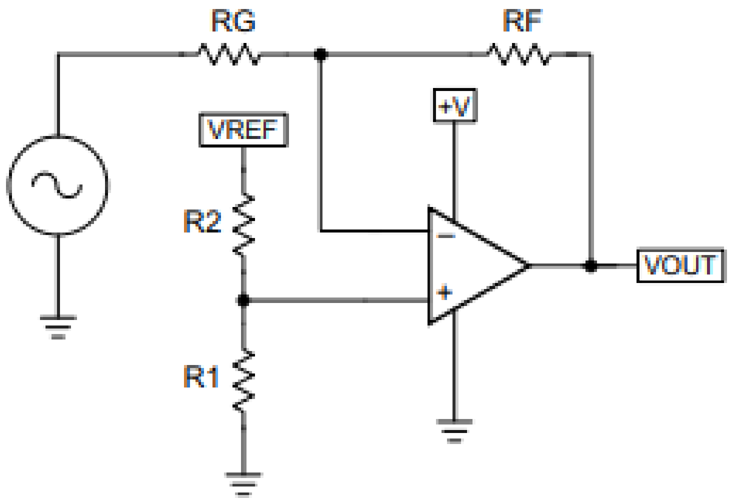


Figure 4.14
Schematic for Case 3: $V_{OUT} = -mV_{IN} + b$.

As m is negative and b are positive, m connected to inverting and b to non inverting

Unit 1 Case 3 example

Circuit has following specifications

V_{OUT} = 1.0V at V_{IN} = -0.1V

V_{OUT} = 6V at V_{IN} = -1V

V_{REF} = 10V

Simultaneous equations

$$1 = (-0.1)m + b$$
$$6 = (-1)m + b$$

From these equations we find that $b = 0.444$ and $m = -5.6$.

$$|m| = 5.56 = \frac{R_F}{R_G}$$
$$R_F = 5.56R_G$$

Let $R_G = 10\ k\Omega$, and then $R_F = 56.6\ k\Omega$,

$$b = V_{CC}\left(\frac{R_F + R_G}{R_G}\right)\left(\frac{R_1}{R_1 + R_2}\right) = 10\left(\frac{56 + 10}{10}\right)\left(\frac{R_1}{R_1 + R_2}\right)$$
$$R_2 = \frac{66 - 0.4444}{0.4444}R_1 = 147.64R_1$$

Unit 1 Case 3 example (continued)

Circuit has following specifications

V_{OUT} = 1.0V at V_{IN} = -0.1V

V_{OUT} = 6V at V_{IN} = 1V

V_{REF} = 10V

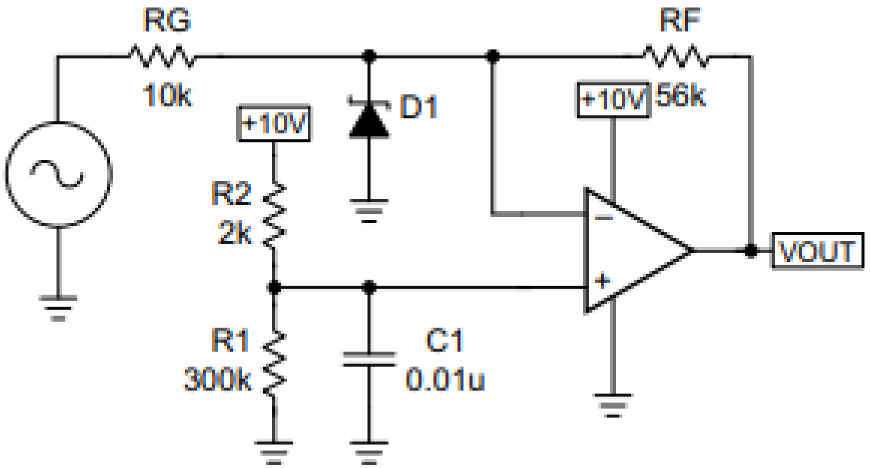


Figure 4.15
Case 3 example circuit.

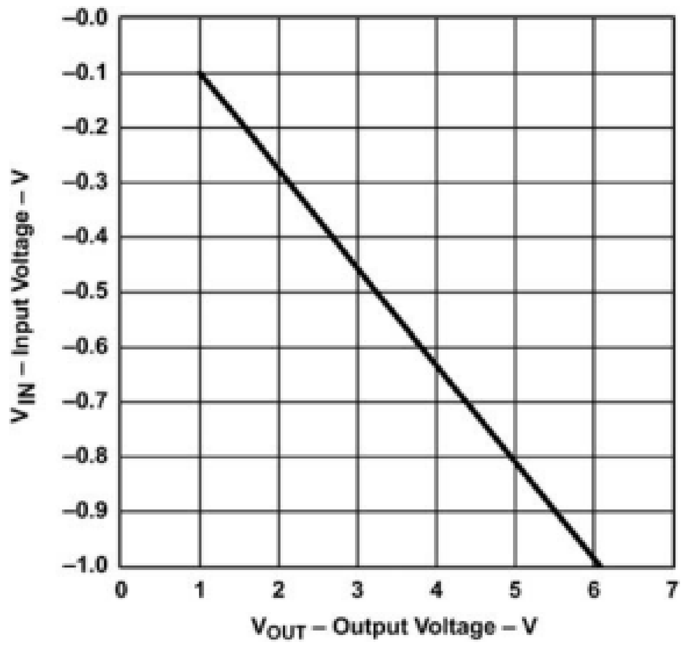


Figure 4.16
Case 3 example circuit measured transfer curve.

Unit 1 Case 4 y = -mx-b

Input connected to inverting input and reference connected to inverting

$$V_{OUT} = -V_{IN}\frac{R_F}{R_{G1}} - V_{REF}\frac{R_F}{R_{G2}}$$

$$|m| = \frac{R_F}{R_{G1}} \qquad |b| = V_{REF}\frac{R_F}{R_{G2}}$$

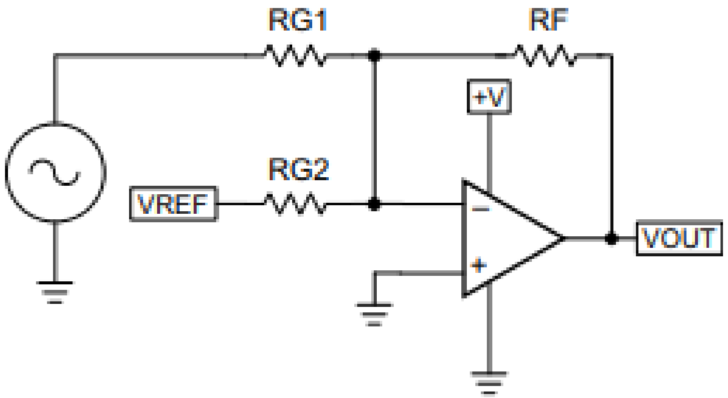


Figure 4.17
Schematic for Case 4: $V_{OUT} = -mV_{IN} - b$.

Unit 1 Case 4 example

Circuit has following specifications
V_{OUT} = 1.0V at V_{IN} = -0.1V
V_{OUT} = 5V at V_{IN} = -0.3V
V_{REF} = 5V

Simultaneous equations

$$1 = (-0.1)m + b$$
$$5 = (-0.3)m + b$$

From these equations we find that $b = -1$ and $m = -20$.

$$|m| = 20 = \frac{R_F}{R_{G1}}$$
$$R_F = 20R_{G1}$$

Let $R_{G1} = 1\ k\Omega$, and then $R_F = 20\ k\Omega$.

$$|b| = V_{CC}\left(\frac{R_F}{R_{G1}}\right) = 5\left(\frac{R_F}{R_{G2}}\right) = 1$$
$$R_{G2} = \frac{R_F}{0.2} = \frac{20}{0.2} = 100\ k\Omega$$

Unit 1 Case 4 example (continued)

Circuit has following specifications

$V_{OUT} = 1.0V$ at $V_{IN} = -0.1V$

$V_{OUT} = 6V$ at $V_{IN} = -0.3V$

$V_{REF} = 5V$

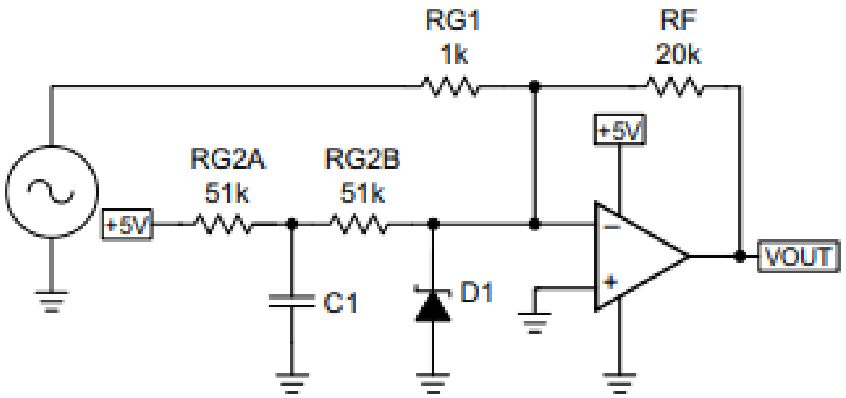


Figure 4.18
Case 4 example circuit.

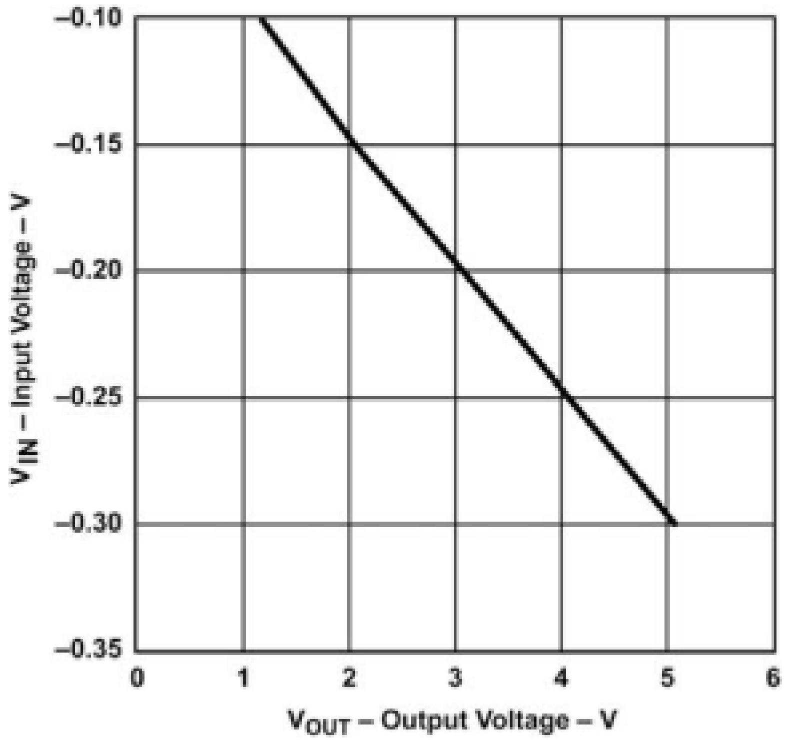


Figure 4.19
Case 4 example circuit measured transfer curve.

Unit 1 Numericals

Example on Finite Gain (Calculate gain for the below two cases)

Case 1 Best case

R_i = 2Kohm

R_s = 200ohm

R_o = 2ohm

R_L = 8ohm

A_{oc} = 500

Case 2 Worst Case

R_i = 500ohm

R_s = 200ohm

R_o = 10ohm

R_L = 8ohm

A_{oc} = 200

Unit 1 Inverting Op amp

Design an amplifier with a gain of 26 dB and an input impedance of 47 kΩ.

Design a simple difference amplifier with an input impedance of 10 kΩ per leg, and a voltage gain of 26 dB.

Reference

- Op Amp for Everyone : Bruce Carter and Ron Mancini Fifth Edition 2017
- Operational amplifiers and linear ICs by James M Fiore 2016
- Design with operational amplifiers and analog integrated circuits by Sergio Franco Fourth Edition 2015

THANK YOU

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