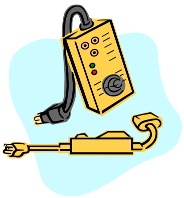
BASIC AMPLIFIERS WITH OP-AMP

I. OBJECTIVES

a) Determination of the gain for the inverting, non-inverting and differential amplifiers.
b) Determination of the causes that lead to the limitation of the amplifiers output voltage (saturation of the amplifier).



II. COMPONENTS AND INSTRUMENTATION

Use the experimental board containing a 741 OP-AMP and different resistors. The differential supply of the board is achieved using a double dc regulated voltage supply. The input voltage is obtained from the signal generator. To visualize the voltage waveforms, a dual-channel oscilloscope is used, and for measuring the dc voltages, a dc voltmeter is used.

The connection diagram of the 741 IC terminals is given in Experiment *Voltage comparators with operational amplifiers – simple comparators*.

III. THEORETICAL ASPECTS

The op amp can be also used as an amplifier. For this it is necessary to connect some circuit elements around the op amp, into a negative feedback (NF) configuration, so that v_D will be kept to zero, $v_D = 0$.

The model of an ideal op amp used as amplifier is presented in Fig. 1. We mention that this model does not include the supply sources, but one of the output terminals is identical with the common terminal (usually ground) of the two supply sources.

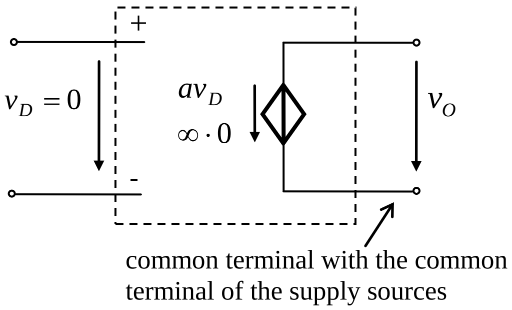


Fig. 1. The model of an ideal op amp as amplifier.

In the case of an op amp, we can obtain NF by feeding back a fraction of the output voltage to the inverting input by means of a voltage divider, as one can see in Fig. 2. In the divider, we used impedances, meaning that in order to have NF we can use any circuit elements (R, C, D, T, etc). The Z_2 impedance closes the loop around the op amp, this is way such a configuration is also known as closed-loop configuration.

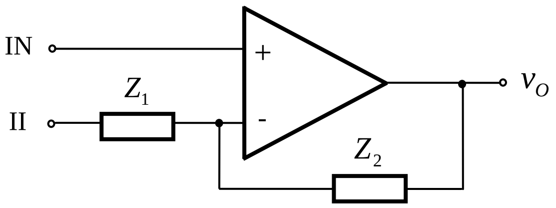


Fig. 2. Op amp with negative feedback.

Op-Amp Amplifiers

In this paragraph we will treat the circuits with op amp and NF, independent of frequency, meaning that Z_1 and Z_2 (in Fig. 2.) are pure resistive (R_1 and R_2). The two inputs (IN – noninverting input; II - inverting input) are not yet connected (are “in the air”). One can connect an input source v_I, between these inputs, (Fig. 3.) as a floating source (without any grounded terminal).

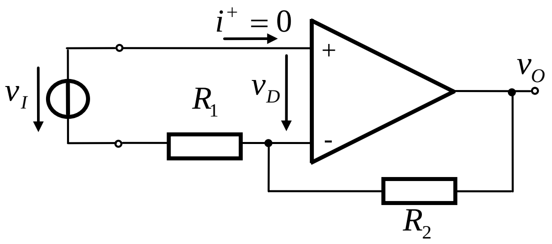


Fig. 3. Op-amp amplifier

Because through the op-amp inputs does not flow any current, the voltage drop across R_1 is zero, resulting $v_D = v_I$. Therefore $v_D \neq 0$ that leads to the conclusion that by applying the floating source v_I

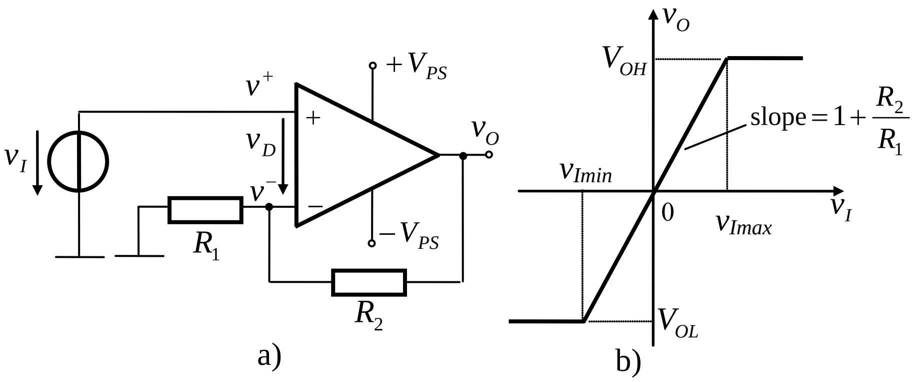


Fig. 4. Noninverting amplifier: a) circuit; b) VTC.

between the two inputs, $v_D \neq 0$, so the circuit does not operate as an amplifier but as a comparator.

Getting back to the circuit in Fig. 2., what other possibilities do we have to connect the signal sources to the circuit? Theoretically, there are three possibilities, synthesized in Table 1.

Table 1.

Inputs		Amplifier
NI	II	
v_I	ground	noninverting
ground	v_I	inverting
v_{I1}	v_{I2}	differential

1. Noninverting Amplifier

The circuit diagram of the noninverting amplifier with is presented in Fig. 4. a).

Let us show first the way the negative feedback (R_1 and R_2) operates to keep $v_D = 0$ V. We remind that $v_D = v^+ - v^-$. We use the relationship of the resistive divider to determine v^- :

$$v^- = \frac{R_1}{R_1 + R_2} v_O$$

Let us assume that for a certain reason v_D tends to increase. Then we have:

$$v_D \uparrow\ ,\ v_O \uparrow\ ,\ v^- \uparrow\ ,\ v_D \downarrow$$

When v_D tends to increase the circuit response is a decrease of v_D. In this way, the op amp with negative feedback tries to do its best to keep v_D zero. This happens only as long as the op amp remains in the active region.

- **Gain**

To determine the gain of an op-amp amplifier with negative feedback (also called *closed-loop gain*), we determine the v_D expression using the assumption of the ideal op-amp:

- there is no current flow through the op-amp inputs (in fact these currents are many times smaller that the other currents in the circuit so that they can be neglected in the current nodes)
- the op-amp own gain, *a*, is infinite.

Then, the condition v_D =0 gives the voltage gain:

$$A_v = \frac{v_O}{v_I}$$

For the amplifier in the Fig. 4. a) we have:

$$v_D = v^+ - v^- = v_I - \frac{R_1}{R_1 + R_2} v_O = 0$$

$$v_I = \frac{R_1}{R_1 + R_2} v_O$$

$$\frac{v_O}{v_I} = \frac{R_1 + R_2}{R_1}$$

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

Alternately, we can determine the gain as follows. Because $v_D = 0$ and $v^+ = v_I$, it results that $v^- = v_I$ (Fig. 4.a)). As there is no current flow through the inverting input, there will be the same current flowing through R_1 and R_2. The current through R_1 is $\frac{v_I}{R_1}$ and the current through R_2 is $\frac{v_O - v_I}{R_2}$.

$$\frac{v_I}{R_1} = \frac{v_O - v_I}{R_2}$$

The same gain expression results:

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

We note that the gain is simply given by the ratio of two resistances R_1 and R_2. It means that we can make the gain as accurate as we want by selecting resistors of appropriate accuracy. It also means that the gain is independent of op amp (own op-amp gain), being not influenced by the technological dispersion of the values of op-amp parameters. These properties are a direct consequence of using NF in the case of an amplifier with a very high value of its own gain ($a \to \infty$ in the case of an op amp).

The amplifier VTC consists of a straight line crossing the origin, with the slope A_v, clipped off at the upper and lower side by the op-amp saturation voltages, as it is shown in Fig. 4.4.4b).

The maximum and minimum values of the input voltage for which the op amp remains in the active region are:

$$v_{I_{max}} = \frac{V_{OH}}{A_v} = \frac{V_{OH}}{1 + \frac{R_2}{R_1}}; \qquad v_{I_{min}} = \frac{V_{OL}}{A_v} = \frac{V_{OL}}{1 + \frac{R_2}{R_1}}$$

- **Input and Output Resistances**

The input resistance of the noninverting amplifier is the equivalent resistance seen by the input signal source when it „looks” towards the amplifier, and the output resistance is the equivalent resistance seen by the load when it „looks” back towards the amplifier.

In order to find the values of these resistances we use the small-signal equivalent circuit as it is shown in Fig. 5. The model of an ideal op amp used as amplifier (see Fig. 1.) replaces the op-amp.

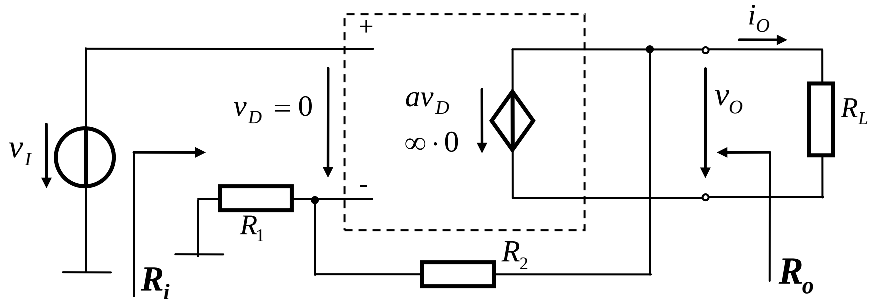


Fig. 5. The small signal equivalent circuit of the noninverting amplifier.

By circuit inspection we observe that v_I sees an open-circuit, meaning that $R_i = \infty$.

To derive the output resistance we determine first the output short-circuit current, so we set $R_L = 0$. In this case the output of the controlled source is short-circuited, meaning an infinite current throughout the source, $i_{O_{sc}} = \infty$. It follows

$$R_o = \frac{v_{O_{gol}}}{i_{O_{sc}}} = \frac{v_{O_{gol}}}{\infty} = 0$$

Thus, at the input and output ports, the noninverting amplifier behaves like an ideal voltage amplifier, $R_i = \infty$ and $R_o = 0$.

Going back to the initial amplifier in Fig. 4.a) we can ask ourselves: „How does this amplifier operate if one or both resistances extreme values, meaning 0 or ∞?” The answer can be found analyzing each case, firstly the existence of the NF and then computing the gain, if possible. For example, if $R_1 = 0$, the inverting input will be grounded, the potential v^- can not be influenced anymore by the value of v_O. Thus, the NF disappears, the circuit becoming a simple comparator.

The joy of discovering the other cases is left for the reader; we will only show the situation in Fig. 6 when $R_1 = \infty$ and $R_2 = 0$. Now we have a unitary-gain amplifier, $A_v = 1$, as $v_I = v^+ = v^- = v_O$, where v^+ and v^- are the op-amp input potentials. Because the entire output voltage is fed back to the inverting input we say that the circuit has *total NF*.

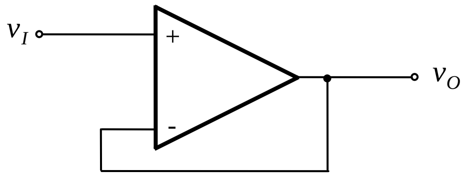


Fig. 6. Voltage follower.

Usually, the circuit is called *voltage follower* because the output follows the input voltage. In spite of no voltage gain, we have an infinite current gain, because the current taken from the signal source is zero while a load connected at the output can draw an important current from the amplifier output. The voltage follower plays the role of a buffer stage to connect a source (or the output of a circuit) with a high output resistance (can supply low current) to a low load resistance (which needs high current).

2. Inverting Amplifier

The inverting amplifier with op amp is shown in Fig. 7. The input source v_I is applied towards the inverting input through the R_1 resistor. The noninverting input is tied to ground.

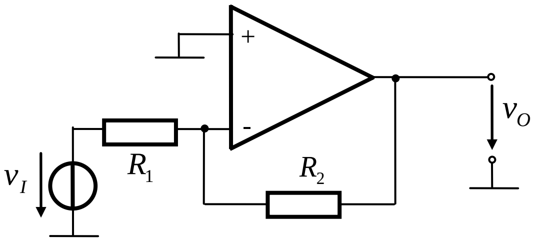


Fig. 7. Inverting amplifier

The circuit has NF because the potential at the inverting input depends on v_I but also on v_O through the $R_1 - R_2$ divider.

To deduce the gain we determine the expression of v_D. Because no current flows into the positive input, we have (Fig. 8.a)):

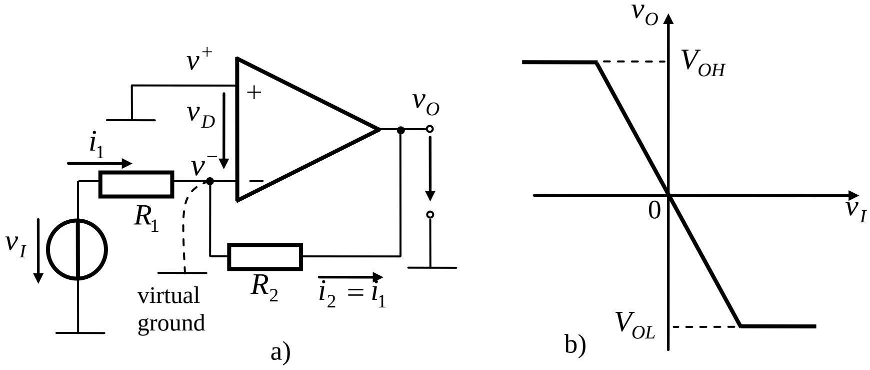


Fig. 8. The inverting amplifier analysis: a) circuit; b) VTC.

$$v^+ = 0\,;\; v^- = \frac{R_2}{R_1 + R_2} v_I + \frac{R_1}{R_1 + R_2} v_O$$

$$v_D = v^+ - v^- = 0 - \frac{R_2}{R_1 + R_2} v_I - \frac{R_2}{R_1 + R_2} v_O = 0$$

The voltage gain for the inverting configuration results as:

$$\boldsymbol{A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}}$$

An alternative for understanding how the circuit operates is the following. Because $v_D = 0$, it results that $v^+ = v^-$. As $v^+ = 0$ and the inverting input is grounded, it results that $v^- = 0$. Because the connection point of the inverting input and the resistors has the potential equal to the ground, without being physically connected to the ground it is called *virtual ground* point. We graphically represented the concept of virtual ground by connecting this point to the ground with a broken line in Fig. 8.a). Through R_1 and R_2 flows the same current, $i_1 = i_2$:

$$i_1 = \frac{v_I - 0}{R_1}\,;\; i_2 = \frac{0 - v_O}{R_2}$$

$$\frac{v_I}{R_1} = -\frac{v_O}{R_2}$$

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

The minus sign shows the inverting character of the amplifier, that is at an increase (decrease) of v_I we have a decrease (increase) of v_O.

The VTC represented in Fig. 8.b) crosses the origin, has a negative slope $\left(-\frac{R_2}{R_1}\right)$ in the active region and it is limited by the saturation voltages of op amp.

- **The Input and Output Resistances**

In Fig.. 8.a) the source v_I sees only the resistance R_1 when it looks towards the circuit, because of the of virtual ground point at the noninverting input. Therefore, the input resistance is:

$$R_i = R_1$$

In comparison with the noninverting amplifier where $R_i = \infty$, for the inverting amplifier we have a finite input resistance. Usually, the order of magnitude of this resistance is units of KΩ, tens of KΩ. If an application requires a higher input resistance, we should use the noninverting configuration.

The output resistance results in the same way as it did at the noninverting amplifier: $R_o = 0$

3. Differential Amplifier

The differential amplifier is used to amplify the difference between two electric signals $v_{I1} - v_{I2}$. The circuit of a differential amplifier with op amp is presented in Fig. 9.

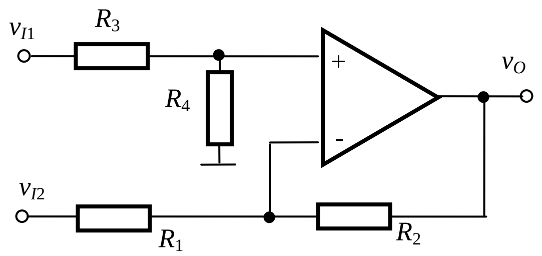


Fig. 9 Differential amplifier.

There are several methods to find out the relation between the output voltage v_O and the input voltages v_{I1} and v_{I2}. To make our life easier we shall use here the superposition method (the circuit is linear).

1) We keep v_{I1} active and set v_{I2} to zero. The equivalent circuit is shown in Fig. 10..a).

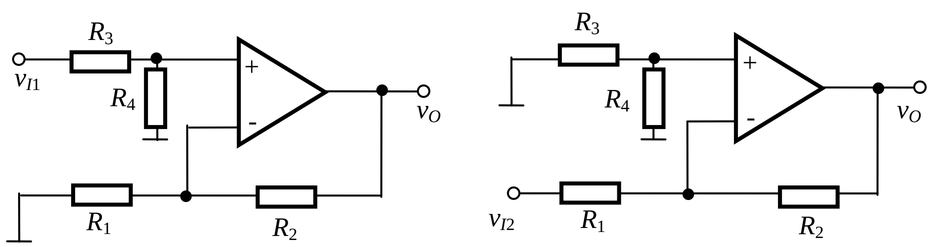


Fig. 10. The superposition method for the differential amplifier:
a) v_{I1} – active and v_{I2} set to 0; b) v_{I2} active and v_{I1} set to 0.

We recognize the noninverting amplifier having an extra divider $R_3 - R_4$ through which we fed-in v_{I1}. The partial output voltage v_{O1} is:

$$v_{O1} = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)v_{I1}$$

2) We keep v_{I2} active and set v_{I1} to 0. The equivalent circuit is shown in Fig. 10.b). The partial output voltage v_{O2} is:

$$v_{O2} = -\frac{R_2}{R_1}v_{I2}$$

The superposition method urges us to add all the partial results to find the final solution.

$$v_O = v_{O1} + v_{O2} = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)v_{I1} - \frac{R_2}{R_1}v_{I2}$$

At first sight, the circuit does not amplify the difference v_{I1}-v_{I2}, but presents some coefficients in front of each voltage. If op amp persuades the resistances to act as the coefficients became equal to each other, then we will have:

$$\frac{R_4}{R_3 + R_4}\left(1+\frac{R_2}{R_1}\right)=\frac{R_2}{R_1}$$

which leads to the condition:

$$\frac{R_1}{R_2}=\frac{R_3}{R_4}$$

The v_O voltage has now the expression:

$$v_O=\frac{R_2}{R_1}\left(v_{I1}-v_{I2}\right)$$

So the difference voltage $v_{I1}-v_{I2}$ is amplified R_2/R_1 times. We notice that for $v_{I1}=v_{I2}$ we obtain $v_O=0$, which means that the circuit amplifies only the difference of the input voltages and *rejects the common mode signals*.

To simplify matters and for other practical considerations one may make $R_1=R_3$ and $R_2=R_4$.

IV. PREPARATION

1.P. INVERTING AMPLIFIER

1.1.P. WAVEFORMS. THE SATURATION OF THE AMPLIFIER

For this paragraph, use the circuit from Fig. 11.

a)

- Which is the value of the voltage gain A_v?
- What does $v_O(t)$ look like for $v_I(t)$ a sinusoidal voltage with 1KHz frequency and 1V amplitude? What about for 2V amplitude?

b)

- Which is the value of A_v, if R^- is 44K ?
- What does $v_O(t)$ look like for R^-=44K and v_I=2sin2□1000t[V][Hz]?

c)

- The dc voltage supply is changed to ±10V.
- Find the input voltage value for which the op-amp enters the saturation region.
- What does $v_O(t)$ look like, in this case, for R^-=22K, $v_I=\sin 2\pi 1000t$[V][Hz] ?

1.2.P. VTC

- What does the VTC look like for the circuit in Fig. 11?
- How does the VTC change if R^- = 44KΩ ?
- What is the range of v_O values?

2.P. NON-INVERTING AMPLIFIER

2.1.P. WAVEFORMS

- What is the value of the voltage gain for the circuit from Fig. 12?
- Determine the output voltage $v_O(t)$ waveform for $v_I(t)$ a sinusoidal voltage with 1V amplitude and 1KHz frequency. What about for an input voltage of 2V amplitude?
- If R=0, what is the value of the voltage gain?

2.2.P. VOLTAGE TRANSFER CHARACTERISTIC (VTC)

- What does the VTC look like for the circuit in Fig. 12?
- How does the above VTC change if R^- = 44KΩ?

3.P. THE DIFFERENTIAL AMPLIFIER

3.1.P. WAVEFORMS

For the differential amplifier from Fig. 13, the differential input voltage is: $v_{Id}=v_{I1}-v_{I2}$.

- What is the value of $A_v=v_O/v_{Id}$ for the circuit in Fig. 13?

- Determine the output voltage $v_O(t)$ waveform if v_{I1}=0.5sin2□1000t[V][Hz] and v_{I2}=0.5V-dc. Redraw $v_O(t)$, considering v_{I1}=0.5V-dc and v_{I2}=0.5sin2π1000t[V][Hz].

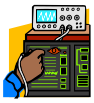
V. EXPLORATIONS AND RESULTS

1.INVERTING AMPLIFIER

1.1. WAVEFORMS. THE SATURATION OF THE AMPLIFIER

Build the circuit shown in Fig. 11.

a)



Exploration

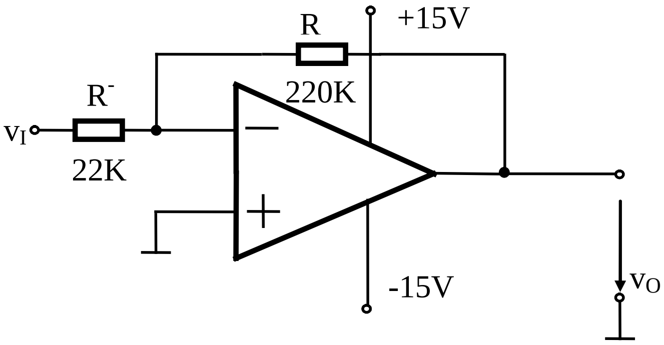


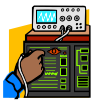
Fig. 11. Inverting amplifier

- $v_I(t)$-sinusoidal signal with 1KHz frequency, obtained from the signal generator.
- With the oscilloscope on the Y-t mode, visualise $v_I(t)$ and $v_O(t)$ for the amplitude of v_I equal with 1V and 2V.

Results

- Draw the waveforms of $v_I(t)$ and $v_O(t)$ for v_I with amplitude of 1V and 2V.
- From the waveform obtained for v_I with 2V amplitude, find the range of values for v_I in order to avoid the saturation of the op-amp (the maximum undistorted output signal).

b)



Exploration

- R^- = 44K (by connecting in series two 22KΩ resistances).
- Visualise $v_I(t)$ and $v_O(t)$ for $v_I(t)$ =2sin2π1000t [V][Hz].

Results

- Draw the waveforms of v_I and v_O.
- What is the value of the voltage gain?

c)

Exploration

- The voltage supply is changed to ±10V.
- Visualise $v_I(t)$ and $v_O(t)$ for $v_I(t)$-sinusoidal voltage with 1KHz frequency and 1V amplitude; $R^- = 22K\Omega$.

Results

- Draw the waveforms of $v_I(t)$ and $v_O(t)$.
- How does the voltage supply influence the range of v_O values?

1.2. VOLTAGE TRANSFER CHARACTERISTIC (VTC)

Exploration

Build the circuit shown in Fig. 11.

- $v_I = 5\sin 2\pi 500t$[V][Hz] obtained for the signal generator.
- With the oscilloscope on the Y-X mode, visualise $v_O(v_I)$.
- Modify R^- to 44KΩ by connecting in series two resistances of 22KΩ.
- Visualise $v_O(v_I)$.

Results

- Draw the VTC for $R^- = 22K\Omega$ and $R^- = 44K\Omega$.
- What are the maximum and the minimum values of v_O?

2.NON-INVERTING AMPLIFIER

2.1.WAVEFORMS

Build the circuit shown in Fig. 12.

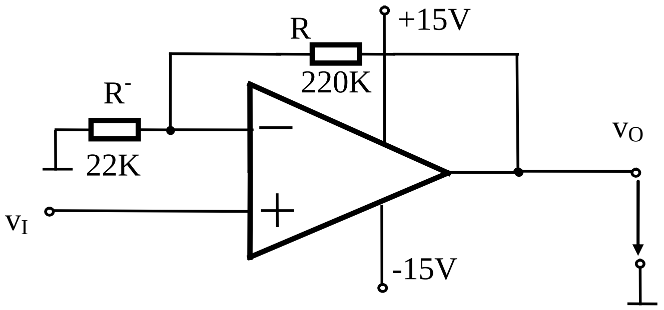


Fig. 12. Non-inverting amplifier

Exploration

- $v_I(t) = \sin 2\pi 1000t$[V][Hz]-from the signal generator.
- With the oscilloscope on the Y-X mode, visualise $v_I(t)$ and $v_O(t)$.
- Repeat the visualisation for v_I with 2V amplitude.
- Draw the circuit that results by short circuiting R(R = 0).
- With the same v_I as above, visualise $v_I(t)$ and $v_O(t)$.

Results

- Draw the $v_I(t)$ and $v_O(t)$ waveforms for v_I with 1V and 2V amplitudes and R=220KΩ, R^-=22KΩ.
- Draw the waveforms for v_I and v_O for R=0; $R^-= \infty$.
- What is the gain of the circuit and what is the name of the amplifier?

2.2.VOLTAGE TRANSFER CHARACTERISTIC (VTC)

Exploration

- Visualise $v_O(v_I)$ on the oscilloscope, for: R^-=22KΩ and R^-=44KΩ

Results

- Draw the VTC for R^-=22KΩ and R^-=44KΩ.
- What are the output voltage values for which the op-amp is saturated?

3.THE DIFFERENTIAL AMPLIFIER

3.1. WAVEFORMS

Exploration

Build the circuit shown in Fig. 13.

- $v_{I1}=0.5\sin 2\pi 1000t$[V][Hz]; v_{I2}=0.5Vdc .

Note: The voltage v_{I2} = 0.5 V d.c. can be obtained using the digital multimeter, set on the 20KΩ domain.

- With the oscilloscope on Y-t mode, visualise $v_I(t)$ and $v_O(t)$.
- Switch the voltages applied to the inputs.
- Visualise $v_{I1}(t)$ and $v_O(t)$.

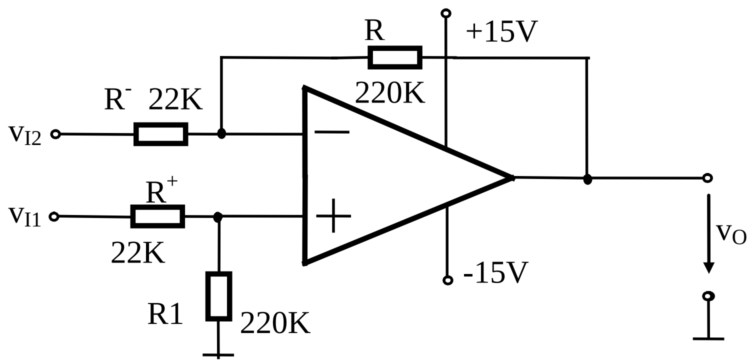


Fig. 13. Differential amplifier

Results

- Draw the waveforms for v_{I1},v_{I2} and v_O in both situation mentioned above.

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