1 The Ideal Opamp

Beginning with ideal opamp is the natural way to understand the analog integrated circuits. Fig.(1) shows the symbol of simplified ideal opamp with three terminals. The terminals v_+ and v_- are called the non-inverting and inverting input terminals and v_o is the output terminal.

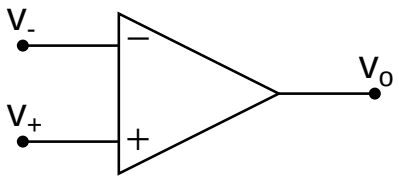


Figure 1: The Basic Operational Amplifier Circuit

The relationship between the input and output terminals is given as,

$$v_o = A(v_+ - v_-). \tag{1}$$

where A is called as the gain of the opamp. The three voltages v_+, v_- and v_o are all measured with respect to ground. The input impedance or R_i is the resistance measured between the inverting and non-inverting terminals. The resistance R_o or the output resistance is the resistance the load would see if it were connected to the output terminal. With these basic definitions we are now ready to see the properties as applied to the ideal opamp.

1.1 Properties of Ideal Opamp

The following are the properties of ideal opamp which should be read with some care as it forms the basis for the opamp analysis. They are worth memorizing as they are frequently used:

1. The gain of the ideal opamp is infinite $A = \infty$.
2. The input impedance is also infinite $R_i = \infty$.
3. The output impedance is zero $R_o = 0$.
4. The bandwidth of the ideal opamp ranges from 0 to ∞.
5. The output of the opamp can source or sink any current and can supply any voltage.

Its quite interesting to note that the properties of practical opamp comes amazingly close to the ideal device.

Let us come back to the original discussion on opamps. It is not hard to see that if the input conditions are such that $v_+ > v_-$ then the output shoots to ∞ and if it is $v_- > v_+$ the output falls to $-\infty$. So the output of opamp stays either at $+\infty$ or $-\infty$. This is not a very exciting result as we would like to build an amplifier that can replicate and amplify a signal. If the amplifier would only stay at infinities it would be no good. Similarly no other useful circuit can be built with the opamp as shown in Fig.(1). The opamp that is operating in this way is said to be in open loop condition. Though there exist circuit applications that operate in open loop the vast majority of the opamp circuits operate in closed loop or in feedback condition.

1.2 The Negative Feedback

The topic of feedback is very vast and wide and is not restricted only to electronic systems. Feedback is evident in chemical, mechanical, economical and even biological systems. For example, many organs in our body use feedback to sustain life. We shall not pretend to learn completely on this ubiquitious and complicated subject. More on it is discussed on courses such as Control Systems. But it is necessary that we learn some important facts about feedback to proceed meaningfully. In doing so we will confine our attention to opamp circuits.

An opamp is said to be in negative feedback condition when a component is connected between the inverting and output terminal. The component could be a resistor, inductor, capacitor or even a transistor. We will frequently see circuits that have a component running between the non-inverting terminal and the output. As you may have guessed, such circuits are said to be in positive feedback condition. Because of the inherent advantages negative feedback condition is more desireable over the positive feedback condition in many linear circuits. Positive feedback circuits do find interesting applications but we will delay the discussion for now.

When we place the opamp in negative feedback condition the output becomes finite. Sometimes this is also seen as an important property of opamps. We also come across circuits that have both negative and positive feedback embedded in it. In such circumstances we start to quantify feedback. If the negative feedback is greater than positive feedback the negative feedback condition prevails in the circuit. Positive feedback prevails if the conditions are the opposite. The circuits that we discuss are in negative feedback unless mentioned otherwise.

1.3 The Inverting Amplifier

We are now ready to analyze our first circuit with opamps. Fig.(2) shows the circuit. We notice that this circuit has a resistor in the feedback path, in particular it is in the negative feedback path.

Now it is established that the circuit is in negative feedback condition, we try to find more information before proceeding. We know that the output is finite, implying

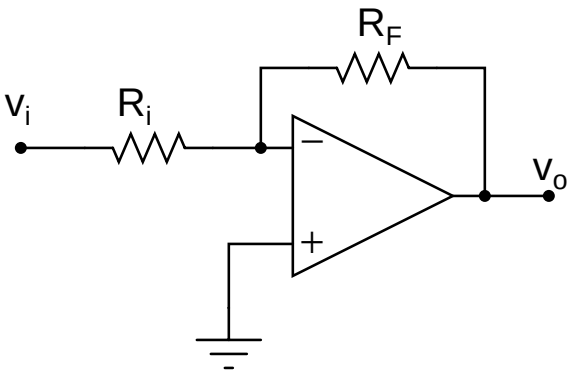


Figure 2: The Inverting Amplifier

$$
\begin{aligned}
A(v_+ - v_-) &= v_0 && (2)\\
A(v_+ - v_-) &= \text{Finite} && (3)\\
(v_+ - v_-) &= \frac{\text{Finite}}{A} && (4)\\
(v_+ - v_-) &= \frac{\text{Finite}}{\text{Infinite}} && (5)\\
(v_+ - v_-) &= 0 && (6)\\
\Rightarrow v_+ &= v_- && (7)
\end{aligned}
$$

This is a remarkable result - in opamp under negative feedback condition the inverting terminal and non-inverting terminal have the same voltage. This phenomenon is called as virtual short. It is as though the inverting terminal and non-inverting terminal have been shorted out - but in reality they are not.

Fig.(3) shows the first steps of analysis for the inverting amplifier. We notice that the non-inverting terminal is grounded. As a consequence of negative feedback, we have

$$v_- = v_+ = 0. \tag{8}$$

This makes the analysis very easy. Now, from Fig.(3) we can apply Ohm's law to get,

$$i_i = \frac{v_i}{R_i}. \tag{9}$$

Next, we use the fact that no current can enter opamp as $R_i = \infty$, hence the only path for the current is through R_F. KCL guarantees that $i_i = i_F$. We also have $v_o = -i_F R_F$ (Note that i_F is flowing in the opposite direction). Hence,

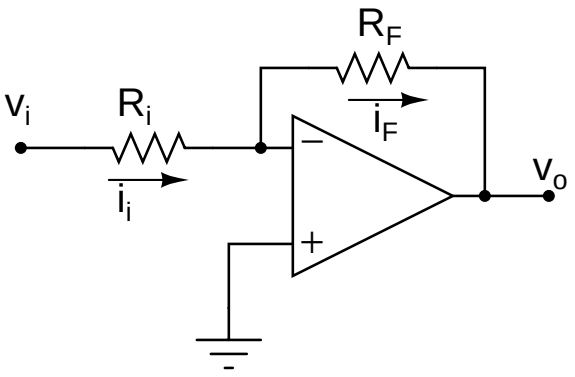


Figure 3: The Inverting Amplifier - analysis

$$
\begin{aligned}
i_i &= i_F && (10)\\
\frac{v_i}{R_i} &= -\frac{v_o}{R_F} && (11)\\
\Rightarrow v_o &= -\frac{R_F}{R_i} v_i && (12)\\
\Rightarrow A_{inv} = \frac{v_o}{v_i} &= -\frac{R_F}{R_i}. && (13)
\end{aligned}
$$

The analysis is straightforward, we only knew the properties of opamp and it is embedded in negative feedback. This amplifier is called as Inverting Amplifier because of the negative sign in the equation for gain. It seems little strange that the gain of opamp A, has little to do with the overall gain A_{inv}. Besides, the overall gain is a ratio of two resistors. We will revisit these issues later.

1.4 The Non-Inverting Amplifier

Fig.(4) shows the circuit of non-inverting amplifier. The only difference is that the roles of the signal v_i and ground have been interchanged.

Fig.(5) shows the analysis steps. Like we did previously, we identify that the circuit is in negative feedback condition and hence the virtual short will apply.

We now have,

$$i_i = \frac{v_i}{R_i} \tag{14}$$

and $i_F = i_i$ from KCL. This time note that from KVL,

$$v_o = i_F R_F + v_i. \tag{15}$$

$v_o \neq i_F R_F$, a common mistake to be avoided. Substituting,

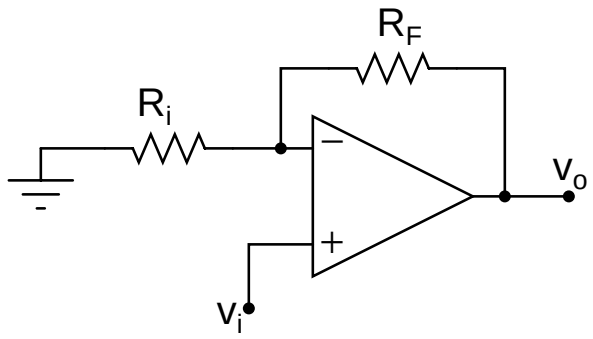


Figure 4: The Non-Inverting Amplifier

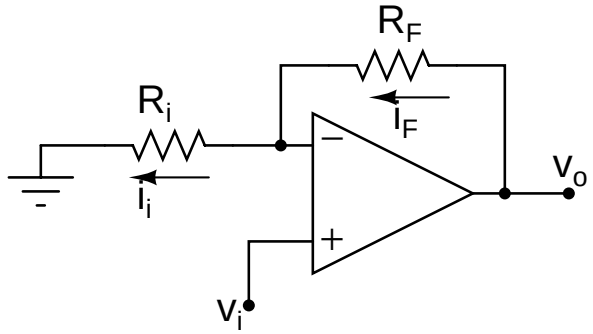


Figure 5: The Non-Inverting Amplifier Analysis Steps

$$
\begin{aligned}
v_o &= i_F R_F + v_i && (16)\\
v_o &= i_i R_F + v_i && (17)\\
v_o &= \frac{v_i}{R_i} R_F + v_i && (18)\\
v_o &= \left(1 + \frac{R_F}{R_i}\right) v_i && (19)\\
\Rightarrow A_{noninv} = \frac{v_o}{v_i} &= \left(1 + \frac{R_F}{R_i}\right). && (20)
\end{aligned}
$$

This time also the gain A_{noninv} is in the form of ratio of resistors but it is distinctly positive making the nomenclature suitable for Non-Inverting Amplifier. An important thing to note is the gain cannot assume values between 0 and 1 as it did in the non-inverting amplifier. Suppose we needed an amplifier of gain 0.25 this Non-Inverting amplifier configuration would not help. This difficulty can be bypassed by using two Inverting amplifiers of gain -0.5 in cascaded fashion. The overall gain is now $A_{cascade} = -0.5 \times -0.5 = 0.25$.

1.5 Solved Problems

1. Fig.(6) shows an ideal opamp in negative feedback condition. Determine v_+, v_- and v_o. Also determine the current through all resistors and the power dissipated by the 6V source.

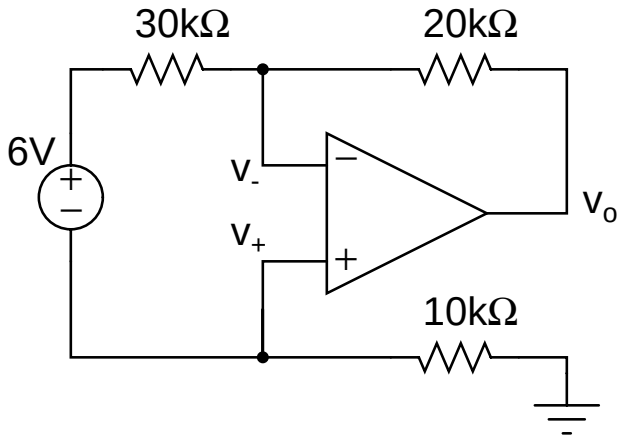


Figure 6: Problem 1

We notice that the opamp input does not absorb any current because of the infinite input impedance. This implies that the current through 30kΩ, 10kΩ and 20kΩ are all the same. This is illustrated in Fig.(7). The same current i flows through 6V battery as it is connected in series with 30kΩ.

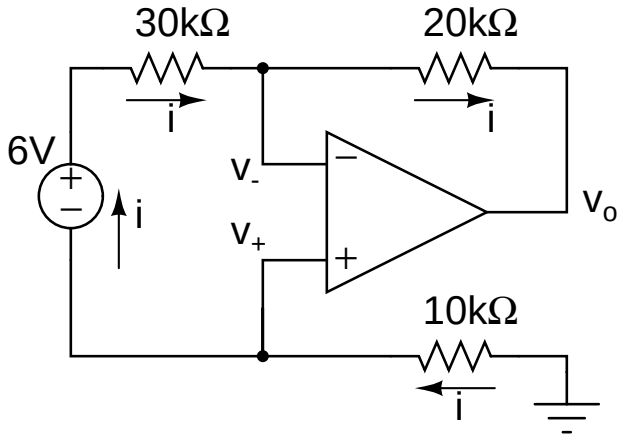


Figure 7: Analysis of Problem 1

Now, the problem reduces to finding i. To find i, we can apply KVL in the loop containing 6V battery, 30kΩ and the input terminals of the opamp. The problem statement says that the opamp is in negative feedback condition, meaning that $v_+ = v_-$. Thus the loop will have only have 6V and 30kΩ. Solving for i, we get

$$30k \times i = 6 \Rightarrow i = 0.2m\text{A}$$

Now, $v_+ = -i \times 10k = -2V$. Negative feedback yields $v_- = -2V$, and $v_o = v_- - 20k \times i$, that is $v_o = -6V$. Finally the power released by the battery is $P = -0.2 \times 10^{-3} \times 6 = -1.2mW$.

2. Fig.(8) shows an ideal opamp in negative feedback condition. Determine v_+, v_- and v_o. Also determine the current through all resistors and the power dissipated by the 4V source. Find the current output by the opamp.

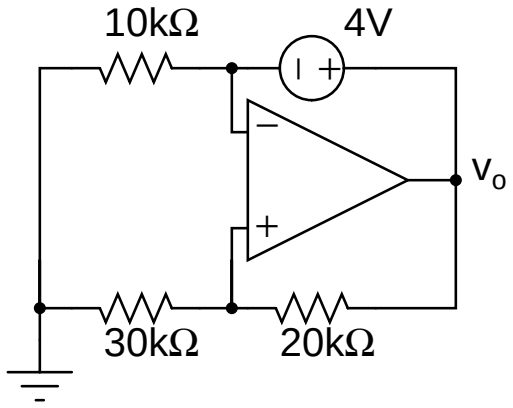


Figure 8: Problem 2

We understand that from $R_i = \infty$ the current through 4V and 10kΩ are the same, namely i_A and likewise the current through 20kΩ and 30kΩ are the same. See Fig.(9) The current output by opamp is $i_A + i_B$. The trick in this problem is in identifying that the voltage difference between v_o and v_+ is the same as the difference between v_o and v_-. That is,

$$\begin{aligned} v_o - v_- &= 4 && (21)\\ v_o - v_+ &= 4 && (22)\\ i_B \times 20 \times 10^3 &= 4 && (23)\\ \Rightarrow i_B &= 0.2m\text{A} && (24) \end{aligned}$$

i_B also flows through 30kΩ resistor which makes $v_+ = 30 \times 0.2 = 6V$. Now, $v_- = 6V$ and hence $i_A = \frac{6}{10} = 0.6m\text{A}$. The power released by the 4V battery is $P = 4 \times 0.6 = 2.4m\text{W}$. The current output by the opamp is $i_o = i_A + i_B = 0.6 + 0.2 = 0.8m\text{A}$. This completes the problem.

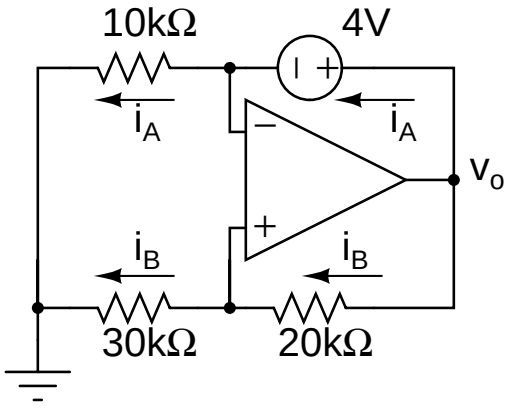


Figure 9: Problem 2: Analysis steps

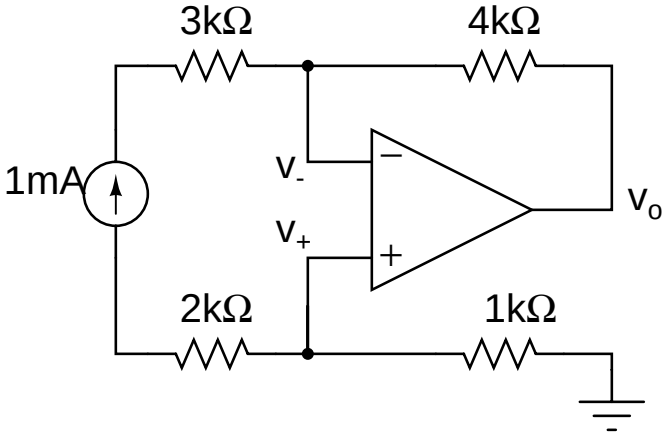


Figure 10: Problem 3

3. Fig.(10) shows an ideal opamp in negative feedback condition. Determine v_+, v_- and v_o

   Using the same arguments as above we notice that the currents through all the reistors to be identical and equal to 1mA. It is straight forward to see that $v_+ = -1$V and $v_- = v_+ = -1$V. Now, $v_o = -1 \times 4 - 1 = -5$V.

1.6 Exercises

1. Fig.(11) shows ideal opamp operating in negative feedback condition. Determine v_+, v_- and v_o. Find the power released by the current source and the current output by the opamp.

   Ans: $v_+ = v_- = -2$V, $v_o = -5V$, $P = 6m$W and $i_o = -0.4m$A.

2. Fig.(12) shows ideal opamp operating in negative feedback condition. Deter-

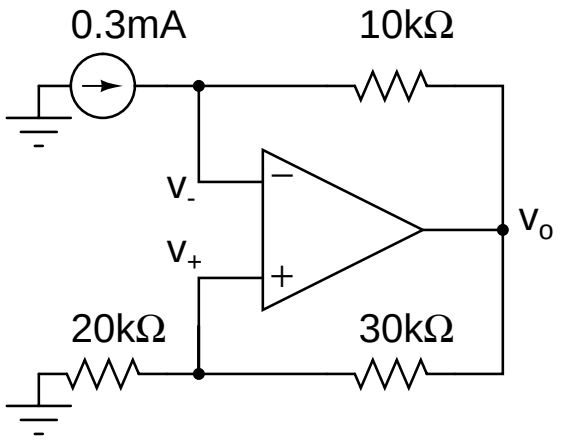


Figure 11: Exercise 1

mine v_+, v_- and v_o.

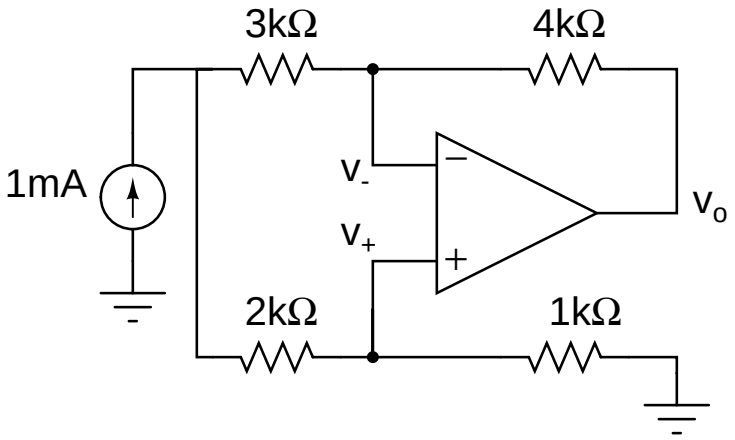


Figure 12: Exercise 2

Ans: $v_+ = v_- = 0.6$V and $v_o = -1V$