MODULE TITLE : DIGITAL & ANALOGUE DEVICES & CIRCUITS

TOPIC TITLE : OPERATIONAL AMPLIFIERS

LESSON 1 : BASIC OPERATIONAL AMPLIFIER CIRCUITS

DADC - 2 - 1

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School of Science & Engineering
Teesside University
Tees Valley, UK
TS1 3BA
+44 (0)1642 342740

INTRODUCTION

The operational amplifier or **op-amp** forms the basic building block of many circuits. It comes as an integrated circuit package and it is cheap and easy to use.

In addition to its function as an amplifier it can be used as a comparator, a buffer, an inverter, a filter or an oscillator. It can also be used to perform mathematical operations such as addition, subtraction, multiplication, division, integration and differentiation. It is clearly a very versatile component!

In this lesson we shall investigate the behaviour of the op-amp in some linear circuits.

YOUR AIMS

At the end of this lesson you should be able to:

- state the properties of the ideal op-amp
- apply the **virtual earth** principle to appropriate op-amp circuits
- understand the use of op-amps as amplifiers and comparators.

The op-amp differs from the conventional amplifier in one very important respect, which is that the op-amp has **two** inputs.

FIGURE 1(a) shows the symbol for the op-amp with its two inputs. One input is called the **inverting** input and the other the **non-inverting** input. They have been labelled '–' and '+' respectively and the corresponding input signals are shown as V_- and V_+ . The output voltage is shown as V_O .

In FIGURE 1(a) the supply voltages have also been shown ($+V_S$ and $-V_S$). Note the dual power supply with typical voltages of +12 V and –12 V. More often than not, the existence of the power supply is taken for granted and the simpler symbol of FIGURE 1(b) is used to represent the op-amp.

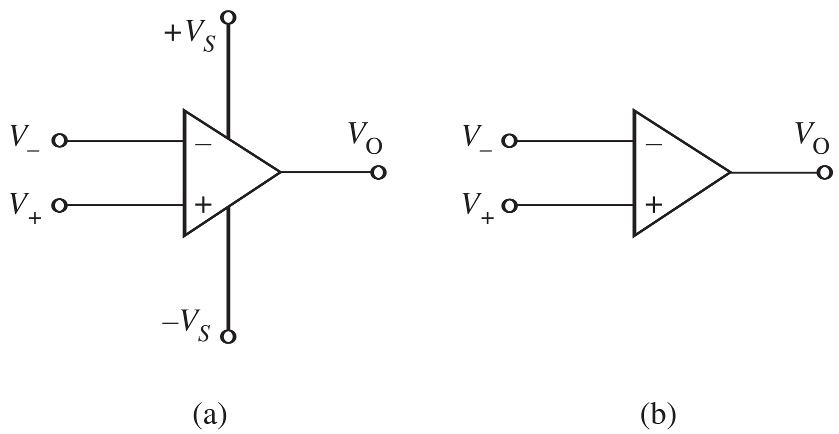

FIG. 1 Circuit Symbols for an Op-amp

Can you suggest reasons for the terms inverting and non-inverting as applied to the

input terminals of the op-amp?

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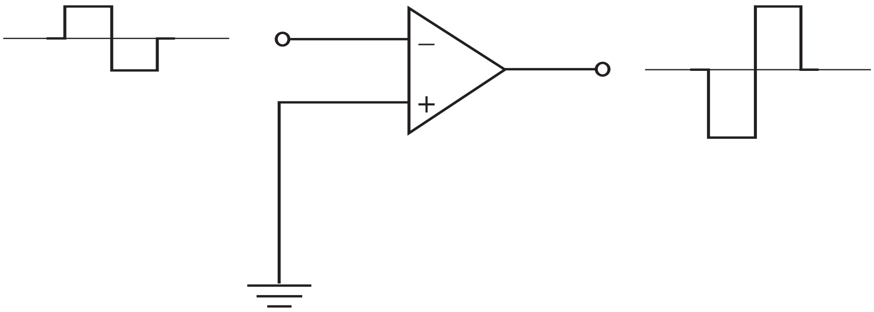
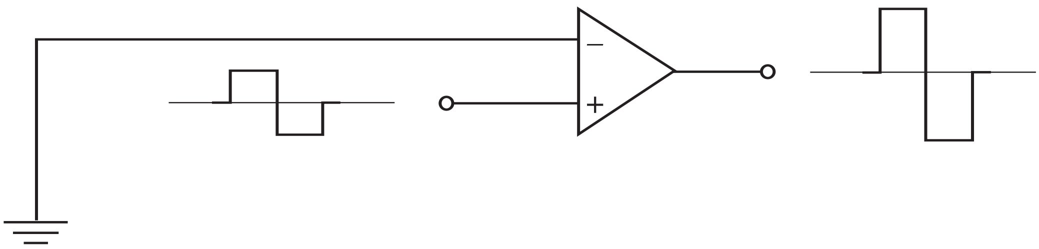
If the voltage on the inverting input is positive, then the voltage at the output will be driven negative, whereas if the voltage on the non-inverting input is positive, then the voltage at the output will be driven positive. FIGURE 2 shows the effect of applying a square wave to each input in turn. When the signal is applied to the inverting input the output is inverted, but not when the signal is applied to the non-inverting input.



(a) Inverting



(b) Non-inverting

FIG. 2 Square Wave Signal applied to each Input

The amplifier will amplify the **difference** between the two input voltages. The output voltage is given by:

$$V_O = G(V_+ - V_-)$$

Where G is known as the open loop differential voltage amplification. The term **open loop** is used to distinguish this value from the voltage amplification of an operational amplifier circuit where the op-amp is used with other components that provide feedback to the amplifier resulting in a **closed loop** amplification.

THE IDEAL OPERATIONAL AMPLIFIER

An ideal op-amp would have:

- an infinite open loop voltage amplification, so that the input voltage $(V_+ - V_-)$ is negligible
- an infinite input impedance, so that the input current will be negligible
- zero output impedance.

TABLE 1 shows a comparison of ideal values and typical values found in practical op-amps.

PARAMETER	*IDEAL VALUE*	*TYPICAL PRACTICAL VALUE*
Open Loop Voltage Amplification	*Infinite*	10^5
Input Impedance	*Infinite*	2 MΩ
Output Impedance	*Zero*	75 Ω

TABLE 1

TABLE 1 shows that a practical op-amp is very close to the ideal. It has a very high open loop voltage amplification, a very high input impedance and a very low output impedance. However, there are practical limitations beyond which the op-amp will cease to behave like the ideal. An important example is the output voltage. In theory, infinite amplification would produce an infinite output signal, however, in practice the output is limited by the supply voltage. The output should not be driven therefore to the positive or negative supply voltage values where amplification is required.

In developing the theory of op-amp circuits, we shall assume an ideal op-amp.

TYPES OF OPERATIONAL AMPLIFIER CIRCUITS

By connecting resistors to the ideal op-amp we can create:

- an inverting amplifier
- a non-inverting amplifier
- a buffer
- a summing amplifier (an adder)
- a difference amplifier.

The Inverting Amplifier

The circuit for an inverting amplifier is shown in FIGURE 3.

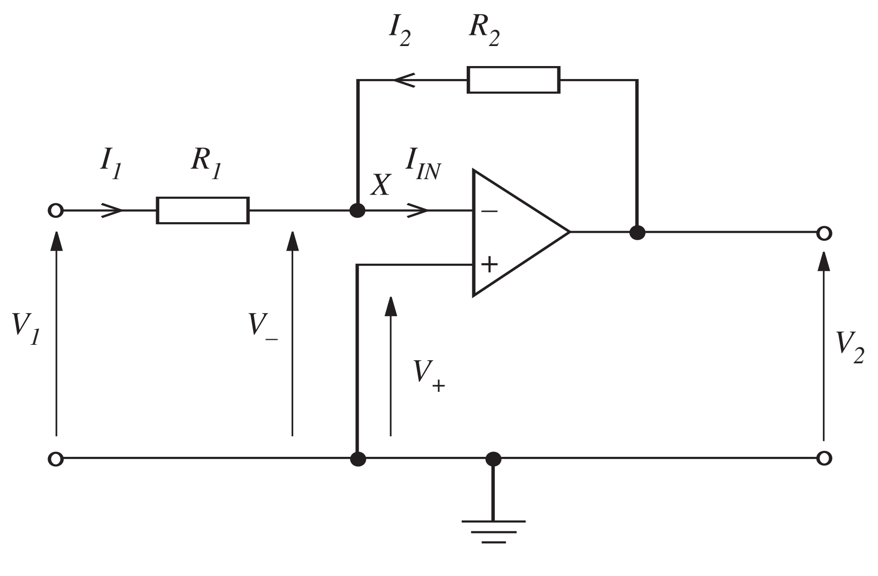


FIG. 3 Inverting Amplifier

The voltage ($V_+ - V_-$) is negligible because the op-amp is assumed ideal and its open loop voltage amplification is infinite.

If the open loop gain of the amplifier is G then:

$$V_2 = G\left(V_+ - V_-\right)$$

$$\frac{V_2}{G} = \left(V_+ - V_-\right)$$

If G tends to infinity, then ($V_+ - V_-$) tends to zero or:

$$\left(V_+ - V_-\right) = 0 \text{ or } V_+ = V_-$$

This means that, for a sensible ouput, there is no voltage difference between the inverting and non-inverting inputs to the op-amp.

By 'sensible output' we mean one that is less than the supply voltage $\pm V_S$. For it is quite possible for, say, $V_- > V_+$ but then the output is drawn towards $-V_S$. Conversely, if $V_- < V_+$ then the output is driven towads $+V_S$.

The current into the inverting terminal and the current out of the non-inverting terminal is also negligible because the ideal op-amp has an infinite input impedance.

In this particular circuit the non-inverting input is connected to earth, therefore:

$$V_+ = 0$$

$$\text{and} \quad V_- = 0$$

The point X must therefore be at earth potential and is known as a **virtual earth**. We can make use of this fact in determining the currents I_1 and I_2.

$$V_1 = I_1R_1 + V_-$$

$$V_1 = I_1R_1 + 0 \qquad \left(\text{virtual earth} \therefore V_- = V_+ = 0\right)$$

$$V_1 = I_1R_1$$

Similarly

$$V_2 = I_2R_2 + V_-$$

$$V_2 = I_2R_2 + 0$$

$$V_2 = I_2R_2$$

The amplification of the circuit is given by:

$$\frac{V_2}{V_1} = \frac{I_2R_2}{I_1R_1}$$

Applying Kirchhoff's law for current at the inverting input we have:

$$I_2 + I_1 = I_{IN}$$

The input current I_{IN} is assumed to be zero however, because the input impedance is infinite. We then have:

$$I_2 = -I_1$$

Substituting this into the expression for the voltage amplification will allow us to cancel the currents giving:

$$\frac{V_2}{V_1} = -\frac{R_2}{R_1}$$

The negative sign shows that the output voltage is inverted relative to the input.

The existence of the virtual earth also means that the input impedance of the amplifier circuit is the resistor R_1.

The circuit employs negative feedback. I_2 is a feedback current which is proportional to the output voltage.

An inverting amplifier is required to give a voltage amplification of 100 and an input resistance of 10 kΩ. Calculate the value of the feedback resistor R_2.

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$$R_1 = 10\ \text{k}\Omega$$

$$\frac{V_2}{V_1} = -\frac{R_2}{R_1}$$

We may ignore the negative sign, since we know that this is an inverting amplifier and so:

$$100 = \frac{R_2}{10 \times 10^3}$$

$$R_2 = 10 \times 10^3 \times 100\ \Omega$$

$$= 1\ \text{M}\Omega$$

The Non-inverting Amplifier

If the inverting input of the amplifier of FIGURE 3 is connected to earth and the input signal applied to the non-inverting input, then the non-inverting amplifier is obtained as shown in FIGURE 4.

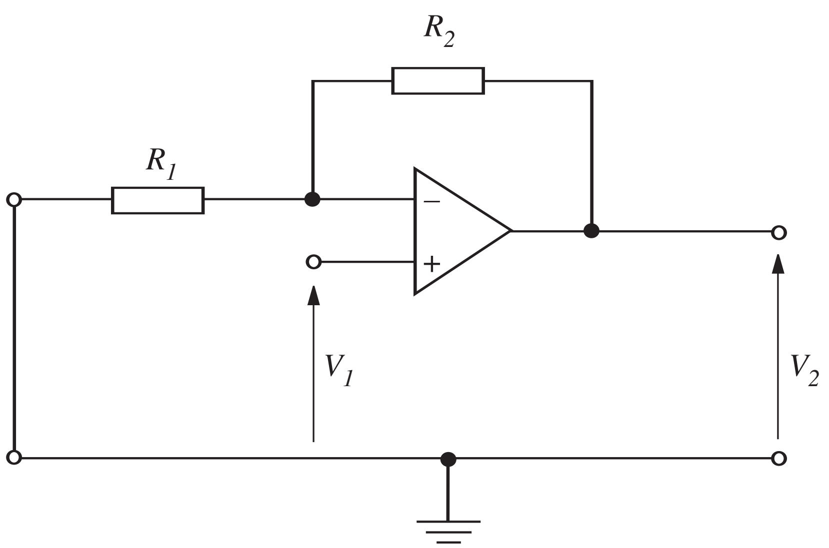

FIG. 4 Non-inverting Amplifier

In a non-inverting amplifier, the output is an amplified version of the input and it is in phase with the input.

The circuit is usually redrawn as in FIGURE 5.

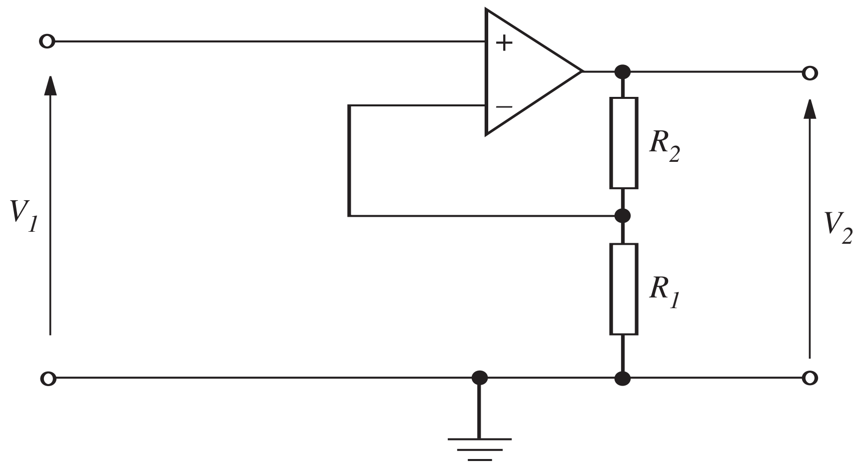

FIG. 5 Non-inverting Amplifier (Redrawn)

Note that neither input is connected to earth. This means that the virtual earth principle cannot be used. The analysis, however, is relatively easy.

R_1 and R_2 form a potential divider, such that:

$$V_- = \frac{R_1}{R_1 + R_2} \times V_2$$

But $V_- = V_+$ because the op-amp is ideal and $V_+ = V_1$ hence:

$$V_1 = \frac{R_1}{R_1 + R_2} \times V_2$$

The voltage amplification of the circuit is:

$$\frac{V_2}{V_1} = \frac{R_1 + R_2}{R_1}$$

Often, R_2 is very much greater than R_1 and in this case:

$$\frac{V_2}{V_1} \approx \frac{R_2}{R_1}$$

The input current drawn from the signal source is also the current into the non-inverting input. Since this current is extremely small, the input resistance is very high (theoretically infinite).

FIGURE 5 is generally used to emphasise that the potential divider provides a feedback voltage which is derived from the output voltage.

Design:

(1) a non-inverting amplifier circuit with R_1 = 5 kΩ and a voltage amplification of 6.

(2) a non-inverting amplifier with a voltage amplification of 100. Assume that R_1 is 10 kΩ.

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1.

$$R_1 = 5 \text{ k}\Omega$$

$$\frac{V_2}{V_1} = \frac{R_1 + R_2}{R_1}$$

$$6 = \frac{5 \times 10^3 + R_2}{5 \times 10^3}$$

$$30 \times 10^3 = 5 \times 10^3 + R_2$$

$$R_2 = 25 \text{ k}\Omega$$

2.

$$R_1 = 10 \text{ k}\Omega$$

$$\frac{V_2}{V_1} = \frac{R_1 + R_2}{R_1}$$

$$100 = \frac{10 \times 10^3 + R_2}{10 \times 10^3}$$

$$1000 \times 10^3 = 10 \times 10^3 + R_2$$

$$R_2 = 990 \text{ k}\Omega \text{ or } 0.99 \text{ M}\Omega$$

In this case we may use the approximate formula. We have:

$$R_1 = 10 \text{ k}\Omega$$

$$\frac{V_2}{V_1} \approx \frac{R_2}{R_1}$$

$$100 \approx \frac{R_2}{10 \times 10^3}$$

$$R_2 \approx 1000 \text{ k}\Omega \text{ or } 1 \text{ M}\Omega$$

Clearly this is a good approximation to the value of 0.99 MΩ obtained previously.

Buffer Circuit

As we have seen, the non-inverting amplifier will have R_2 greater than R_1 to give voltage amplification.

Now let us consider the situation where R_1 is greater than R_2.

$$\frac{V_2}{V_1} = \frac{R_1 + R_2}{R_1}$$

$$\approx \frac{R_1}{R_1} \approx 1$$

Also, the input resistance, which is equal to the input resistance of the op-amp itself, will be very high.

Taking the resistance values to the extreme we replace R_1 by an open circuit and R_2 by a short circuit. This gives the circuit of FIGURE 6 which has unity voltage amplification with a high input resistance and a low output resistance. The circuit therefore may be used as an electrical buffer because it will draw minimum current from a signal source and will be able to provide a large output current to a load.

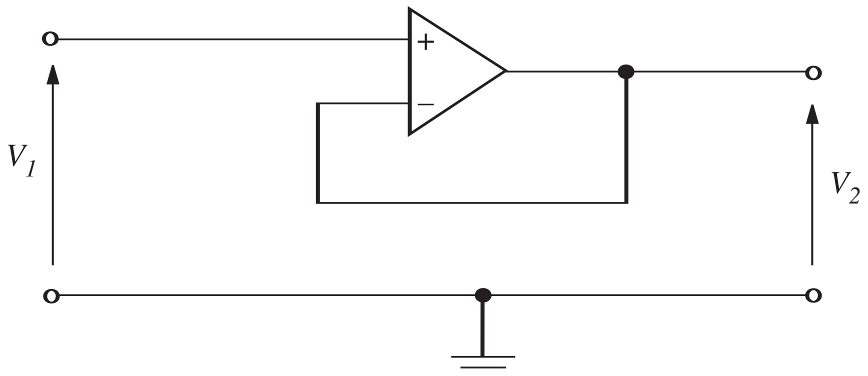

FIG. 6 Buffer Circuit

The buffer is also called a **voltage follower**.

Summing Amplifier

The circuit in FIGURE 7 is essentially an inverting amplifier with two input voltages connected to the inverting input.

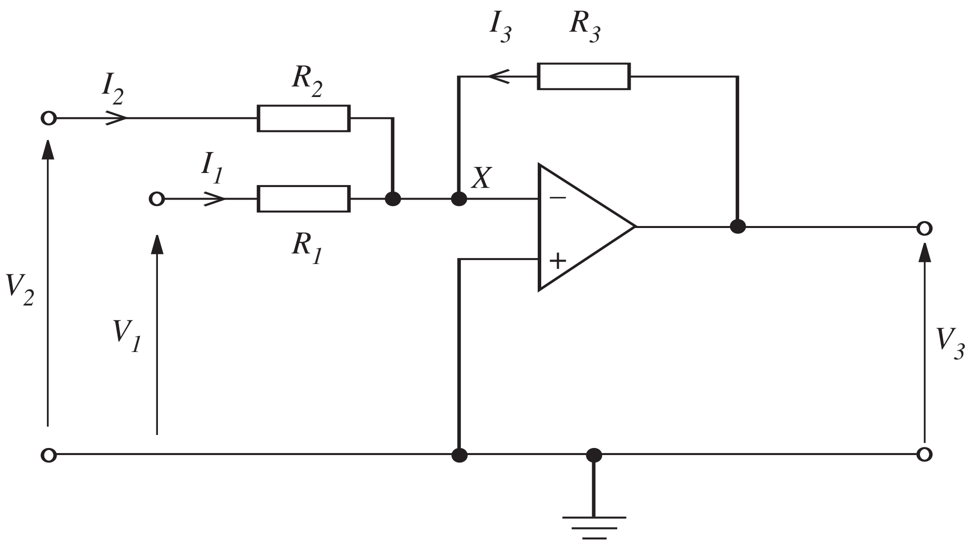

FIG. 7 Summing Amplifier

The non-inverting input is connected to earth, so the concept of a virtual earth at point X can be used. Hence:

$$I_1 = \frac{V_1}{R_1}$$

$$I_2 = \frac{V_2}{R_2}$$

$$I_3 = \frac{V_3}{R_3}$$

Using Kirchhoff's law for currents and the fact that current into the inverting input is negligible, we have:

$$I_1 + I_2 + I_3 = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = 0$$

So in general: $$V_3 = -\frac{R_3 V_1}{R_1} - \frac{R_3 V_2}{R_2}$$

In the case where $R_1 = R_2 = R_3$ then we have:

$$V_3 = -(V_1 + V_2)$$

If $R_1 = R_2 = R$ then: $$V_3 = -\frac{R_3}{R}(V_1 + V_2)$$

The two input voltages have been added and amplified (with inversion) by a factor of $\dfrac{R_3}{R}$.

Difference Amplifier

To obtain an output which is proportional to the difference of two inputs we must use both the non-inverting input and the inverting input. FIGURE 8 shows that the connection to the inverting input is similar to that for the inverting amplifier whilst the connection to the non-inverting input is through a potential divider.

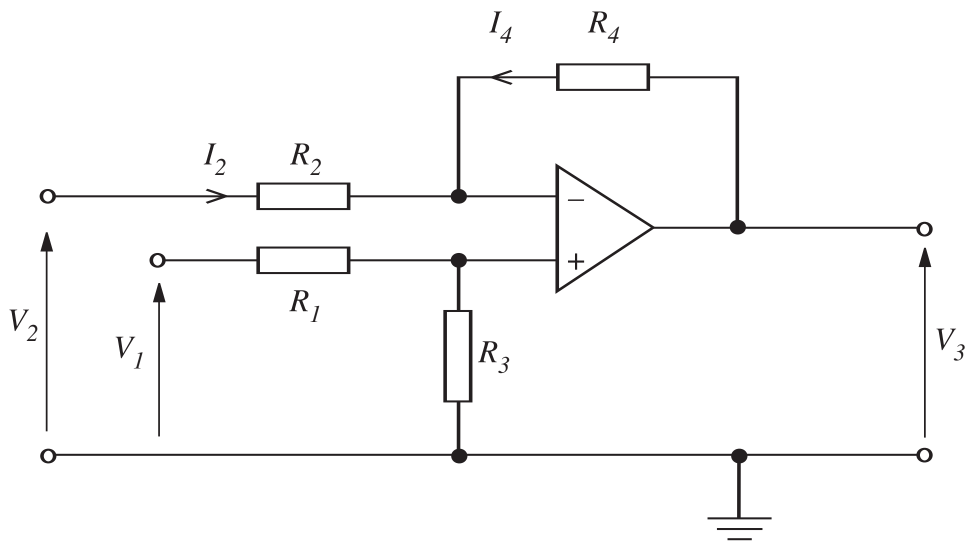

FIG. 8 Difference Amplifier

To keep the analysis simple we shall assume that all the resistors have the same value R.

The circuit does not have a virtual earth. However the sum of the currents I_2 and I_4 will still be zero, as in the inverting amplifier circuit, and hence:

$$I_2 = -I_4$$

also $$I_2 = \frac{V_2 - V_-}{R}$$

Similarly $$I_4 = \frac{V_3 - V_-}{R}$$

so $$\frac{V_2 - V_-}{R} = \frac{V_- - V_3}{R}$$

or $$V_2 - V_- = V_- - V_3$$

$$V_3 = 2V_- - V_2$$

The two resistors at the non-inverting input form a potential divider hence:

$$V_+ = \frac{V_1}{2}$$

We know that: $$V_- = V_+$$

so $$2V_- = V_1$$

Substituting this in the equation for V_3 above

$$V_3 = V_1 - V_2$$

i.e. the output signal is the difference of the input signals.

Often, in practice, the two resistors connecting the input voltages are usually made equal ($R_1 = R_2$) and the feedback resistor and the resistor connecting the non-inverting input to ground are made equal ($R_3 = R_4$).

The output is then:

$$V_3 = \frac{R_4}{R_2}\left(V_1 - V_2\right)$$

(the ratio $\frac{R_4}{R_2}$ represents the amplification applied to the difference of the input signals).

An important advantage in the use of a difference amplifier is that signals which are common to both inputs, e.g. noise, are rejected. This is known as **common mode rejection**. The amplifier is particularly useful where an input is obtained from sensors at a very low signal voltage. Very high amplification is required. In a conventional inverting or non-inverting amplifier the noise would be amplified along with the signal. Using a differential amplifier, the noise is rejected.

Voltage Comparator

We recall that an op-amp can be used to amplify the difference between the two inputs. It is ideal in this mode for comparing two analogue voltages. The principle of operation is shown in FIGURE 9.

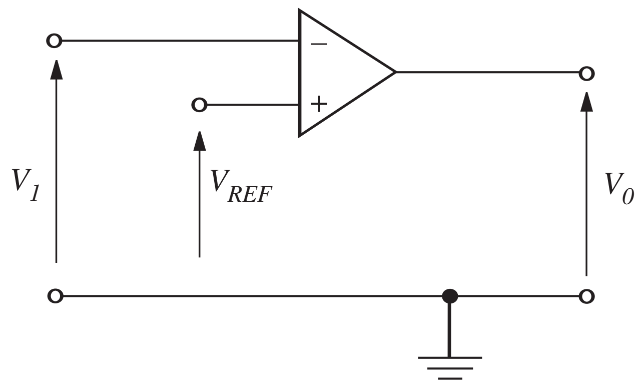

FIG. 9 Simple Comparator

The input voltage V_1 which is connected to the inverting input is compared with a reference voltage V_{REF} connected to the non-inverting input. Any small difference between these voltages is amplified and the output voltage V_2 saturates because the amplification is so high.

If $\quad V_1 < V_{\mathrm{REF}}$ then $V_2 = +V_{\mathrm{SAT}}$

and if $\quad V_1 > V_{\mathrm{REF}}$ then $V_2 = -V_{\mathrm{SAT}}$

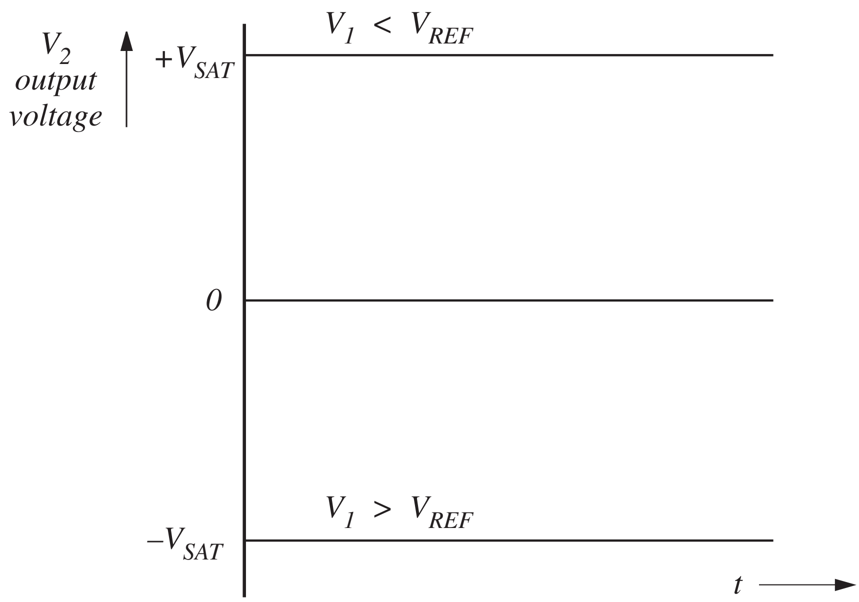

FIG. 10 Output Voltage

The output voltage will switch between the upper and lower limits. It cannot have any value between these two because of the high voltage amplification. Op-amp comparators are widely used in the design of switching circuits such as thermostats and light operated circuits. They are also frequently used as elements in the design of analogue to digital and digital to analogue circuits.

A problem may occur in the use of this comparator circuit if there is a significant noise voltage superimposed on the input voltage. The output may switch low and high several times, as the noise takes the total input above and below the reference value. To avoid this problem we must introduce **hysteresis** into the circuit. Hysteresis is present when the output does not follow the same curve for increasing values of the input as when the input is decreasing. A simple mechanical example of the required characteristic occurs in a toggle switch for a room light. When it is taken past its upper position the contacts snap off and they will only switch on when it is taken past its lower position.

Positive feedback is used as shown in FIGURE 11. (Take care not to confuse this circuit with that for the non-inverting amplifier. The external connections are similar but the connections to the op-amp inputs have been interchanged.)

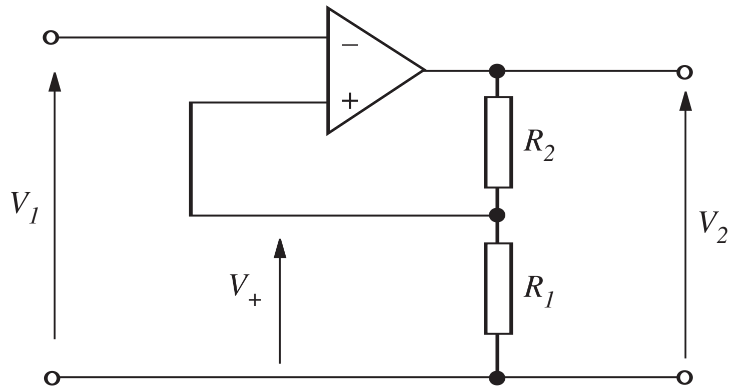

FIG. 11 Op-amp Comparator with Hysteresis (Schmitt Trigger)

This circuit is often called a Schmitt trigger after the man who designed it.

If $\quad V_1 < V_+ \quad$ then $\quad V_2 = +V_{SAT}$

The resistors R_1 and R_2 form a potential divider so that:

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

This value forms the upper threshold level.

Now, if the input voltage increases until it exceeds V_+,

$$V_1 > V_+ \quad \text{and} \quad V_2 = -V_{SAT}$$

$$V_+ = -\frac{R_1}{R_1 + R_2} V_{SAT}$$

This negative value will form the lower threshold voltage.

When interfacing to logic gates, the large output swing ($2V_{SAT}$) and the large negative values are undesirable. In this case a Zener diode may be used as shown in the circuit of FIGURE 12.

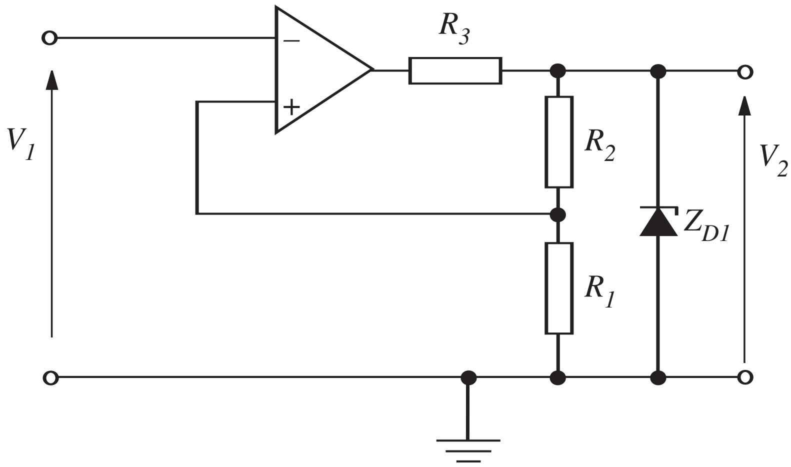

FIG. 12 Op-amp Comparator with Zener Diode

When the output tries to go negative, the Zener diode is forward biased and it conducts. The forward volt drop is approximately 0.7 V for a silicon diode.

When the output tries to go positive the Zener diode is reverse biased and it breaks down. So the output voltage is restricted to the Zener voltage V_Z. The difference between the output of the op-amp and the Zener voltage is dropped across R_3.

Calculate the threshold voltages for the circuit of FIGURE 12 given that:

$$R_1 = 6.8\ \text{k}\Omega$$

$$R_2 = 10\ \text{k}\Omega$$

$$V_Z = 4.7\ V$$

Assume that the forward voltage drop for the Zener diode is 0.7 V.

We may use the expression which was derived for the simple circuit provided that we use the appropriate voltage values.

Feedback is obtained from the Zener voltage and not from the output of the op-amp, such that:

$$\text{upper threshold voltage} = \frac{R_1}{R_1 + R_2} V_Z$$

$$= \frac{6.8}{6.8 + 10} \times 4.7$$

$$= 1.90 \text{ V}$$

When the output of the op-amp is driven low the Zener diode goes into forward conduction. We have then:

$$\text{lower threshold voltage} = -\frac{6.8}{6.8 + 10} \times 0.7$$

$$= -0.28 \text{ V}$$

Semiconductor manufacturers provide comparator ICs which are generally more convenient to use and avoid many of the problems relating to speed of operation and voltage levels which arise in comparator circuits based on op-amps.

NOTES

SELF-ASSESSMENT QUESTIONS

1. An inverting amplifier has an input resistance of 3 kΩ and a feedback resistance of 150 kΩ. Calculate the voltage amplification.

2. FIGURE 13 shows an op-amp circuit with a constant input voltage of +2.4 V connected to the non-inverting input. Calculate the output voltage.

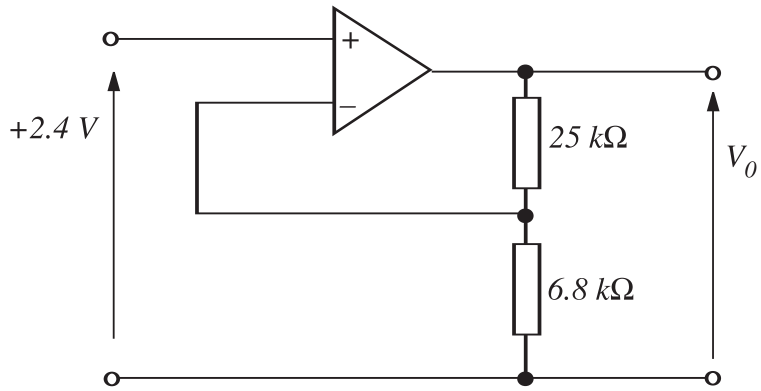

FIG. 13 Op-amp Circuit

3. An amplifier is required to give an output of:

$$V_O = 100V_3 + 10V_2 + V_1$$

Draw a suitable op-amp circuit to give this output. If the feedback resistor is 100 k, calculate the remaining resistance values for the circuit.

4. FIGURE 14 shows the circuit of a difference amplifier.

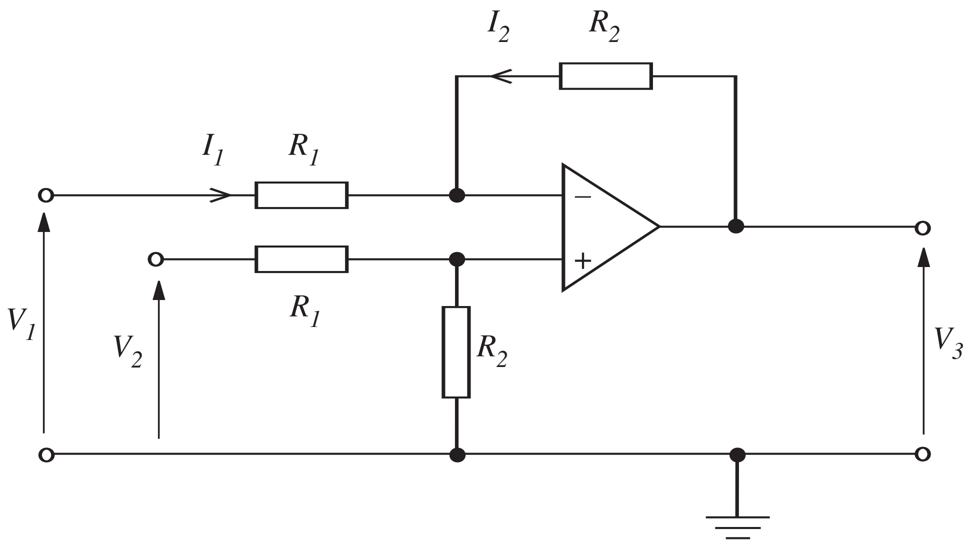

FIG. 14 Difference Amplifier

(a) Write down an expression for V_+ in terms of V_2, R_1 and R_2.

(b) Write down an equation relating the currents I_1 and I_2 in terms of V_-, V_1, V_3, R_1 and R_2.

(c) Write down the relationship between V_+ and V_- , assuming that the op-amp is ideal.

(d) Hence show that:

$$V_3 = \frac{R_2}{R_1}\left(V_2 - V_1\right)$$

5. FIGURE 15(a) shows the input waveform to a comparator with hysteresis. The threshold levels are 0.8 V and 2.0 V as shown on the figure. Complete FIGURE 15(b) to show the output of the comparator. Assume that a high threshold crossing gives a high output.

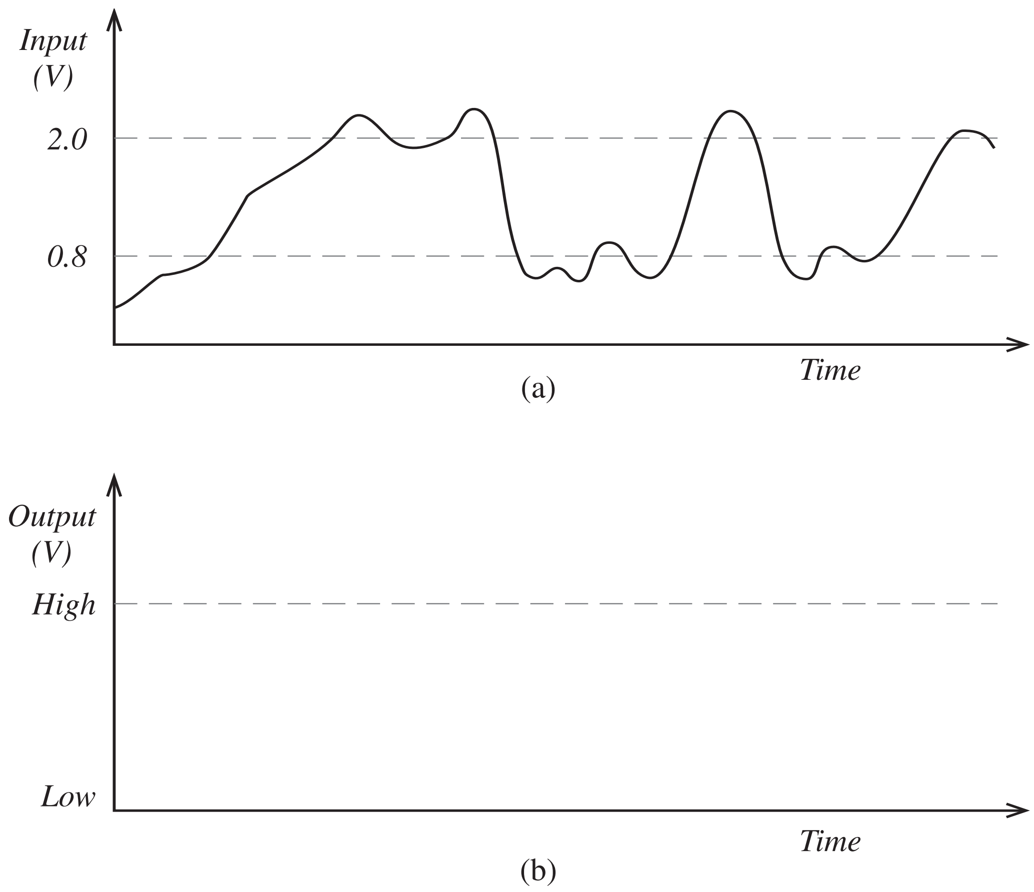

FIG. 15 Comparator Waveforms

NOTES

ANSWERS TO SELF-ASSESSMENT QUESTIONS

1. $$\frac{V_2}{V_1} = -\frac{R_2}{R_1}$$

Hence the voltage amplification is:

$$\frac{V_2}{V_1} = \frac{150 \times 10^3}{3 \times 10^3} = 50$$

2. This is a non-inverting amplifier so:

$$\frac{V_2}{V_1} = \frac{R_1 + R_2}{R_1}$$

$$\frac{R_1 + R_2}{R_1} = \frac{6.8 \times 10^3 + 25 \times 10^3}{6.8 \times 10^3}$$

$$\frac{V_2}{V_1} = 4.7$$

The output voltage will be:

$$2.4 \times 4.7 = 11.3\,\text{V}$$

3. A summing amplifier is required and the circuit is similar to FIGURE 7 but with an additional input V_3 as shown in FIGURE 16.

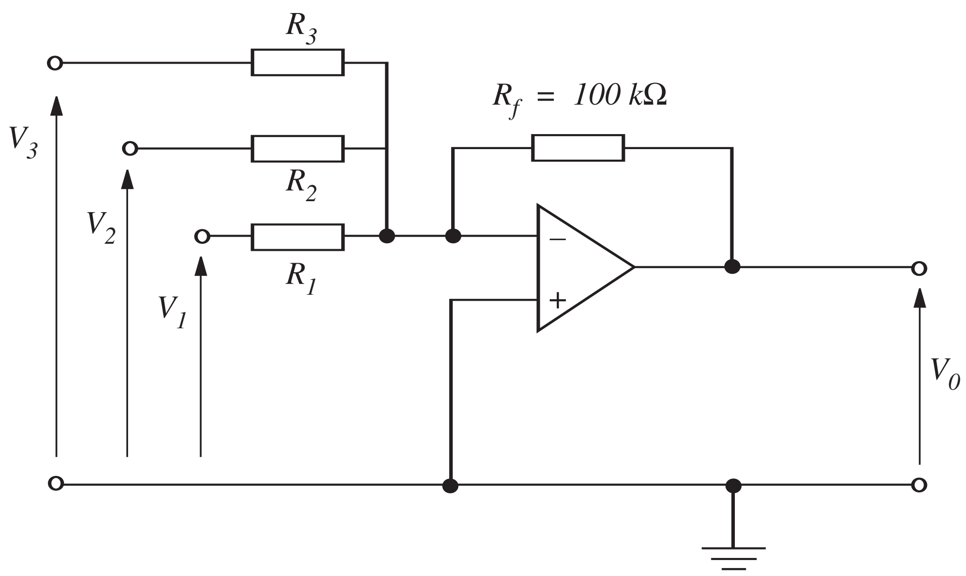

FIG. 16 Summing Amplifier with Three Inputs

The amplification factor for V_3 is 100

Hence
$$100 = \frac{100\ \text{k}\Omega}{R_3}$$

$$R_3 = 1\ \text{k}\Omega$$

Similarly
$$R_2 = 10\ \text{k}\Omega$$

and
$$R_1 = 100\ \text{k}\Omega$$

4. (a) The input to the non-inverting terminal is obtained from the potential divider so:

$$V_+ = \frac{R_2}{R_1 + R_2} V_2$$

(b)

$$I_1 = \frac{V_1 - V_-}{R_1}$$

$$I_2 = \frac{V_o - V_-}{R_2}$$

$$I_1 + I_2 = 0$$

$$\frac{\left(V_1 - V_-\right)}{R_1} + \frac{\left(V_o - V_-\right)}{R_2} = 0$$

(c) $V_+ = V_-$

(d) From part (b)

$$\frac{\left(V_1 - V_-\right)}{R_1} = -\frac{\left(V_o - V_-\right)}{R_2}$$

$$R_2\left(V_1 - V_-\right) = -R_1\left(V_o - V_-\right)$$

$$\left(R_1 + R_2\right)V_- = R_2 V_1 + R_1 V_o$$

Using part (c) we have

$$(R_1 + R_2)V_+ = R_2V_1 + R_1V_o$$

Substituting from part (a) for V_+ gives

$$(R_1 + R_2)\frac{R_2}{(R_1 + R_2)}V_2 = R_2V_1 + R_1V_O$$

$$R_2V_2 = R_2V_1 + R_1V_o$$

$$R_1V_O = -R_2V_1 + R_2V_2$$

This gives the required result:

$$V_O = \frac{R_2}{R_1}(V_2 - V_1)$$

5. FIGURE 17 shows the input and output waveforms of the comparator.

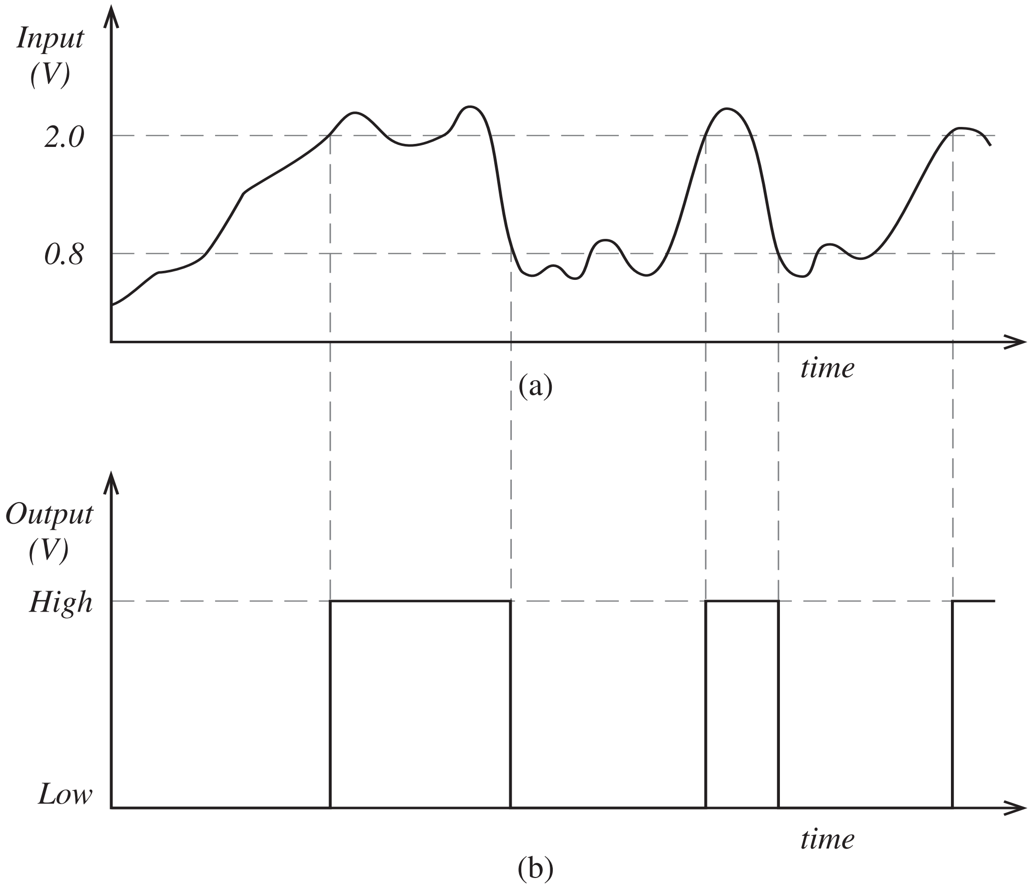

FIG. 17 Comparator Input and Output Waveforms

SUMMARY

The characteristics of an ideal op-amp are:

(i) 'Infinite' voltage amplification
(ii) 'Infinite' input impedance
(iii) 'Zero' output impedance.

For an ideal op-amp the output is finite only if:

$$V_+ = V_-$$

Various amplifier circuits using the operational amplifier have been developed such as:

- Inverting amplifier, using the inverting input and current feedback.
- Non-inverting amplifier, using the non-inverting input and voltage feedback.
- Buffer circuit, with unity amplification and high input impedance.
- Summing amplifier whose output is the sum of two input voltages.
- Difference amplifier whose output is the difference of two input voltages.

Comparators are used to compare an input voltage with a reference voltage and to detect when the reference voltage is equalled. In a comparator the output is usually not symmetrical. In general there is a difference between V_+ and V_-. Hysteresis is often built into a comparator to avoid faulty switching.