LESSON 10 **Operational Amplifiers**

Objectives

By the end of the lesson the student should be able to:

(i) Appreciate the operation amplifier as a building block for many electronic circuits
(ii) Decribe the idealized characteristics of operational amplifier
(iii) Decsribe the different types of operational amplifiers

Operational Amplifiers, or **Op-amps** as they are more commonly called, are one of the basic building blocks of Analogue Electronic Circuits. Operational amplifiers are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation. An ideal **Operational Amplifier** is basically a three-terminal device which consists of two high impedance inputs, one called the **Inverting Input**, marked with a negative sign, ("-") and the other one called the **Non-inverting Input**, marked with a positive plus sign ("+").

The third terminal represents the op-amps output port which can both sink and source either a voltage or a current. In a linear operational amplifier, the output signal is the amplification factor, known as the amplifiers gain (A) multiplied by the value of the input signal and depending on the nature of these input and output signals, there can be four different classifications of operational amplifier gain.

- Voltage – Voltage "in" and Voltage "out"
- Current – Current "in" and Current "out"
- Transconductance – Voltage "in" and Current "out"
- Transresistance – Current "in" and Voltage "out"

Since most of the circuits dealing with operational amplifiers are voltage amplifiers, (Vin and Vout).

The amplified output signal of an Operational Amplifier is the difference between the two signals being applied to the two inputs. In other words the output signal is a *differential* signal between the two inputs and the input stage of an Operational Amplifier is in fact a differential amplifier.

Differential Amplifier

The circuit below shows a generalized form of a differential amplifier with two inputs marked V1 and V2. The two identical transistors TR1 and TR2 are both biased at the same operating point with their emitters connected together and returned to the common rail, -Vee by way of resistor Re.

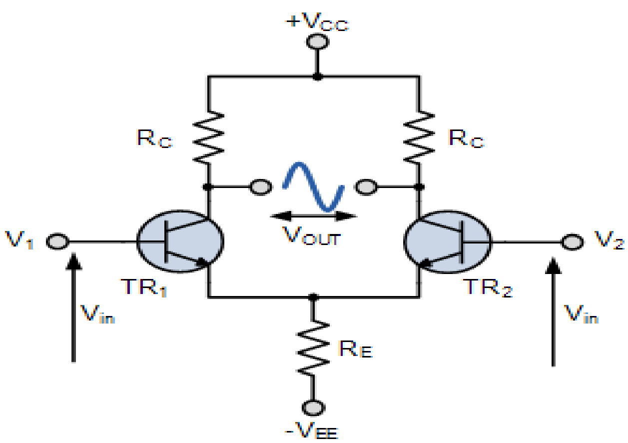


Fig 10.1 Differential Amplifier

Differential Amplifier

The circuit operates from a dual supply +Vcc and -Vee which ensures a constant supply. The voltage that appears at the output, Vout of the amplifier is the difference between the two input signals as the two base inputs are in *anti-phase* with each other. So as the forward bias of transistor, TR1 is increased, the forward bias of transistor TR2 is reduced and vice versa. Then if the two transistors are perfectly matched, the current flowing through the common emitter resistor, Re will remain constant.

Like the input signal, the output signal is also balanced and since the collector voltages either swing in opposite directions (anti-phase) or in the same direction (in-phase) the output voltage signal, taken from between the two collectors is, assuming a perfectly balanced circuit the zero difference between the two collector voltages. This is known as the *Common Mode of Operation* with the **common mode gain** of the amplifier being the output gain when the input is zero.

Equivalent Circuit for Ideal Operational Amplifiers

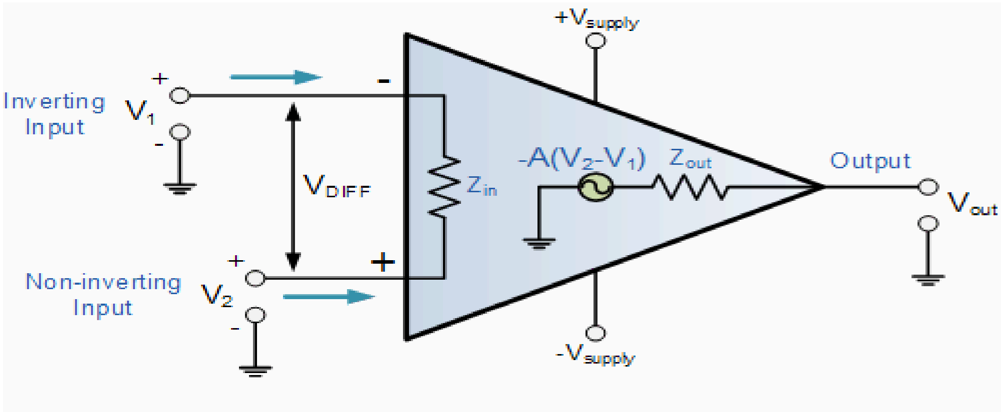


Fig 10.2 Ideal Operational Amplifier Equivalent Circuit

Op-amp Idealized Characteristics

PARAMETER	IDEALIZED CHARACTERISTIC
Open Loop Gain, (Avo)	**Infinite** - The main function of an operational amplifier is to amplify the input signal and the more open loop gain it has the better. Open-loop gain is the gain of the op-amp without positive or negative feedback and for an ideal amplifier the gain will be infinite but typical real values range from about 20,000 to 200,000.
Input impedance, (Z_{in})	**Infinite** - Input impedance is the ratio of input voltage to input current and is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry (Iin =0). Real op-amps have input leakage currents from a few pico-amps to a few milli-amps.
Output impedance, (Z_{out})	**Zero** - The output impedance of the ideal operational amplifier is assumed to be zero acting as a perfect internal voltage source with no internal resistance so that it can supply as much current as necessary to the load. This internal resistance is effectively in series with the load thereby reducing the output voltage available to the load. Real op-amps have output-impedance in the 100-20Ω range.

Bandwidth, (BW)	**Infinite** - An ideal op amp has an infinite frequency response and can amplify any frequency signal from DC to the highest AC frequencies so it is therefore assumed to have an infinite bandwidth. With real op-amps, the bandwidth is limited by the Gain-Bandwidth product (GB), which is equal to the frequency where the amplifiers gain becomes unity.
Offset Voltage, (V_{io})	**Zero** - The amplifiers output will be zero when the voltage difference between the inverting and the non-inverting inputs is zero, the same or when both inputs are grounded. Real op-amps have some amount of output offset voltage.

From these "idealized" characteristics above, input resistance is infinite, so **no current flows into either input terminal** (the "current rule") and that the **differential input offset voltage is zero** (the "voltage rule"). These two properties help us understand the workings of the **Operational Amplifier** with regards to the analysis and design of op-amp circuits.

<u>Summing Amplifier Applications</u>

If the input resistances of a summing amplifier are connected to potentiometers the individual input signals can be mixed together by varying amounts. For example, measuring temperature, you could add a negative offset voltage to make the display read "0" at the freezing point or produce an audio mixer for adding or mixing together individual waveforms (sounds) from different source channels (vocals, instruments, etc) before sending them combined to an audio amplifier.

<u>Summing Amplifier Audio Mixer</u>

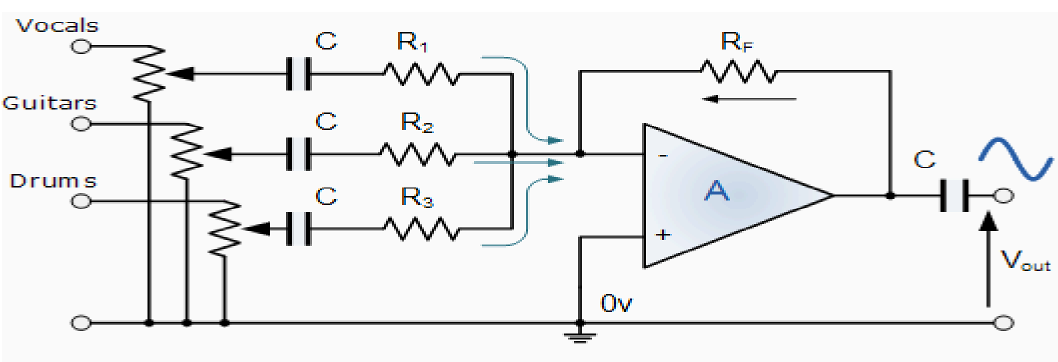


Fig 10.3 Summing Amplifier Audio Mixer

Another useful application of a **Summing Amplifier** is as a weighted sum digital-to-analogue converter. If the input resistors, Rin of the summing amplifier double in value for each input, for example, 1kΩ, 2kΩ, 4kΩ, 8kΩ, 16kΩ, etc, then a digital logical voltage, either a logic level "0" or a logic level "1" on these inputs will produce an output which is the weighted sum of the digital inputs. Consider the circuit below.

Digital to Analogue Converter

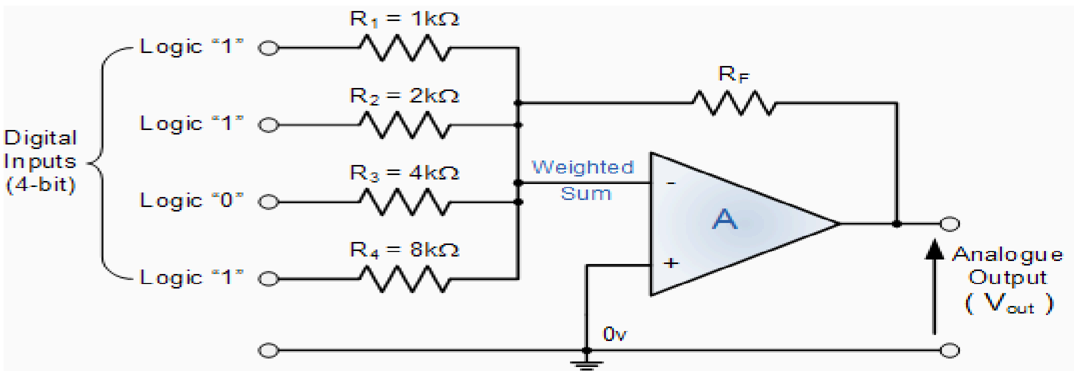


Fig 10.4 Digital Analogue Converter

Of course this is a simple example. In this DAC summing amplifier circuit, the number of individual bits that make up the input data word, and in this example 4-bits, will ultimately determine the output step voltage as a percentage of the full-scale analogue output voltage. Also, the accuracy of this full-scale analogue output depends on voltage levels of the input bits being consistently 0V for "0" and consistently 5V for "1" as well as the accuracy of the resistance values used for the input resistors, Rin. Fortunately to overcome these errors, commercial available Digital-to Analogue and Analogue-to Digital devices are available.

The effect of the output voltage, Vout when a signal voltage is connected to the inverting input and the non-inverting input are inserted at the same time, this produces another common type of operational amplifier circuit called a **Differential Amplifier** which can be used to "subtract" the voltages present on its inputs

Differential Amplifier

Thus far we have used only one of the operational amplifiers inputs to connect to the amplifier, using either the "inverting" or the "non-inverting" input terminal to amplify a single input signal with the other input being connected to ground.

But we can also connect signals to both of the inputs at the same time producing another common type of operational amplifier circuit called a **Differential Amplifier**.

Basically, as we saw that, all op-amps are "Differential Amplifiers" due to their input configuration. But by connecting one voltage signal onto one input terminal and another voltage signal onto the other input terminal the resultant output voltage will be proportional to the "Difference" between the two input voltage signals of V1 and V2. Then differential amplifiers amplify the difference between two voltages making this type of circuit a **Subtractor** unlike a summing amplifier which adds or sums together the input voltages. This type of operational amplifier circuit is commonly known as a **Differential Amplifier** configuration and is shown below:

<u>Differential Amplifier</u>

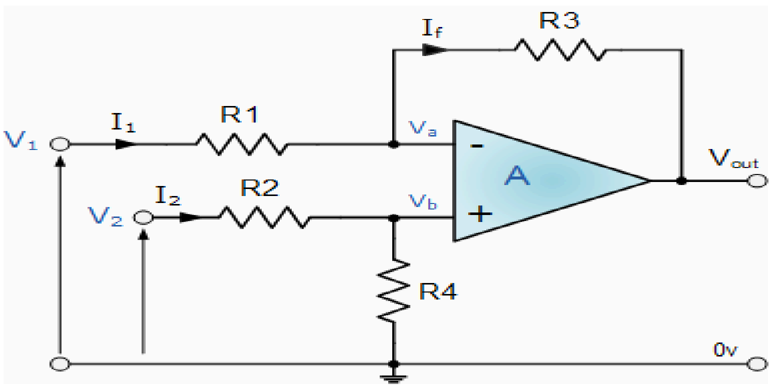


Fig 10.5 Differential Operational Amplifier

By connecting each input in-turn to 0v ground we can use superposition to solve for the output voltage Vout.

The Two Basic Operational Amplifier Circuits

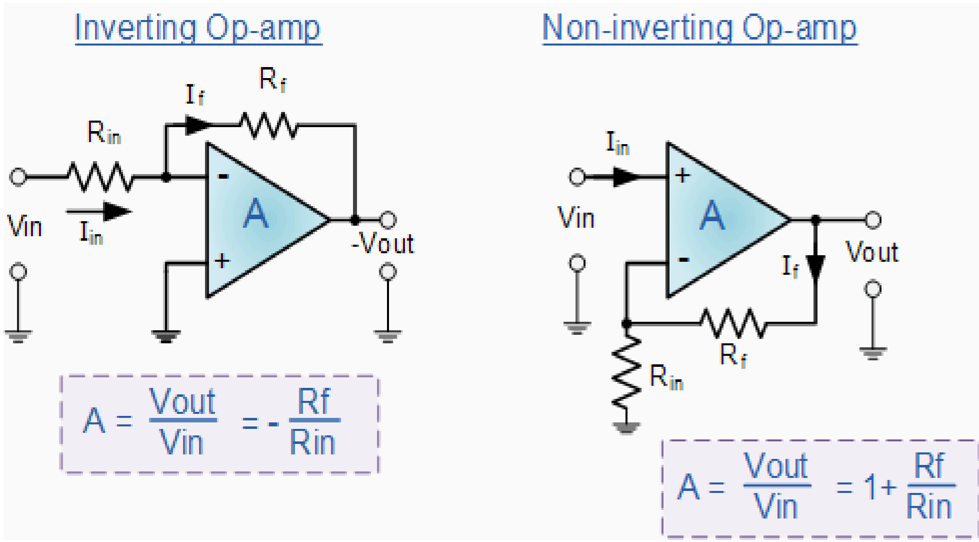


Fig 10.6 Inverting and Non Inverting OP Amp

- The Open-loop gain called the **Gain Bandwidth Product**, or (GBP) can be very high and is a measure of how good an amplifier is.
- Very high GBP makes an operational amplifier circuit unstable as a micro volt input signal causes the output voltage to swing into saturation.
- By the use of a suitable feedback resistor, (Rf) the overall gain of the amplifier can be accurately controlled.
- The **Differential Amplifier** produces an output that is proportional to the difference between the 2 input voltages.

Differential and Summing Operational Amplifier Circuits

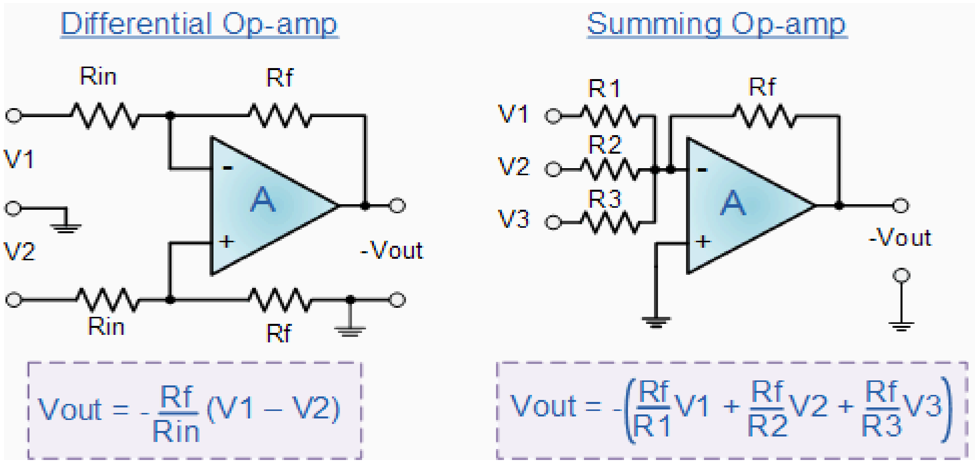


Fig 10.7 Differential and summing Op Amp

Adding more input resistor to either the inverting or non-inverting inputs **Voltage Adders** or **Summers** can be made.

- Voltage follower op-amps can be added to the inputs of Differential amplifiers to produce high impedance Instrumentation amplifiers.
- The **Integrator Amplifier** produces an output that is the mathematical operation of integration.
- The **Differentiator Amplifier** produces an output that is the mathematical operation of differentiation.
- Both the Integrator and Differentiator Amplifiers have a resistor and capacitor connected across the op-amp and are affected by its RC time constant.
- In their basic form, Differentiator Amplifiers suffer from instability and noise but additional components can be added to reduce the overall closed-loop gain.

Differentiator and Integrator Operational Amplifier Circuits

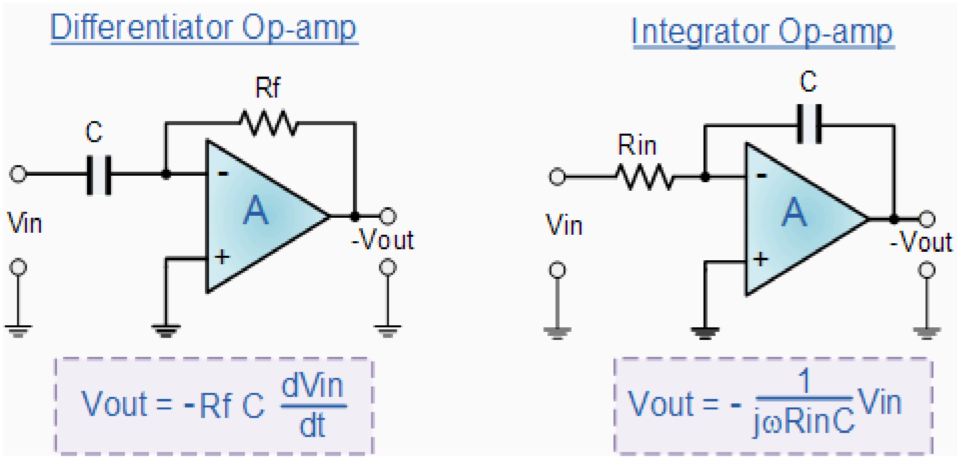
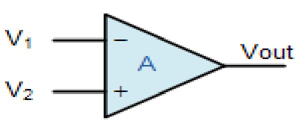


Fig 10.8 Differentiator and Integrator Op Amp

Operational Amplifiers Summary

We know now that an **Operational amplifiers** is a very high gain DC differential amplifier that uses one or more external feedback networks to control its response and characteristics. We can connect external resistors or capacitors to the op-amp in a number of different ways to form basic "building Block" circuits such as, Inverting, Non-Inverting, Voltage Follower, Summing, Differential, Integrator and Differentiator type amplifiers.



Op-amp Symbol

Fig 10.9 OP Amp Symbol

An "ideal" or perfect Operational Amplifier is a device with certain special characteristics such as infinite open-loop gain Ao, infinite input resistance Rin, zero output resistance Rout, infinite bandwidth 0 to ∞ and zero offset (the output is exactly zero when the input is zero).