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Course Catalogue Description

1. Modelling an Op-Amp.
2. Op-Amp input modes.
3. Need for feed backs in Op-Amps.
4. Effect of negative feedback.
5. Ideal Op-Amp Characteristics.
6. Op-Amp configurations and applications.
7. Op-Amp parameters

Op-Amp

Operational Amplifier

An Operational Amplifier is a directly coupled, active circuit element with high voltage gain and high input impedance designed to perform mathematical operation.

The Op-Amp is a Differential Amplifier with a differential-input and a single-ended-output. The circuit symbol or representation of the Op-Amp and pins is as shown in Figure 1.

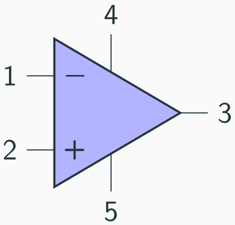


Figure 1: Circuit Symbol of the Op-Amp

Modelling an Op-Amp

In strict mathematical sense, we write

$$V_{out} = A_V(V_1 - V_2) \quad (1)$$

where A_V is the open-loop voltage gain and is determined entirely by the Op-Amp internal circuitry. The open-loop gain is always specified in the Op-Amp specification sheet with values ranging from 10^5 to 10^8.

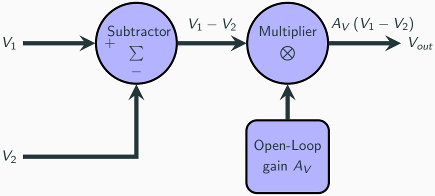


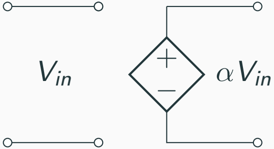
Figure 2: Functional Block Diagram of an Op-Amp

Dependent Sources

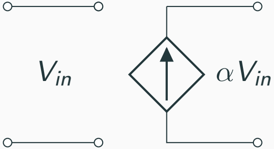
A dependent source is a voltage or current source whose output value termed source is controlled by a voltage or current somewhere else (usually on the input side) in the circuit. Dependent sources help to model complex electrical circuits like the Op-Amp. There are four categories of dependent sources. They include:

1. Voltage Controlled Voltage Source;
2. Current Controlled Voltage Source;
3. Voltage Controlled Current Source; and
4. Current Controlled Current Source.

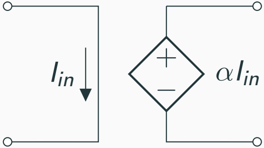
Op-Amps will be modeled as a dependent source and we choose the Voltage Controlled Voltage Source of Figure 3(a).



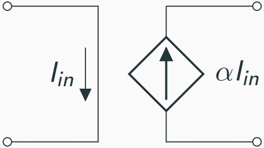
(a) Voltage Controlled Voltage Source



(b) Voltage Controlled Current Source



(c) Current Controlled Voltage Source



(d) Current Controlled Current Source

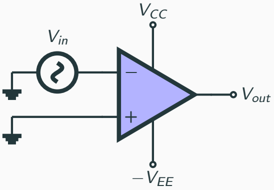
Figure 3: Dependent Sources

Op-Amp input modes

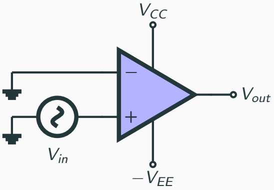
The Op-Amp is an extension of the Differential Amplifier and can also be connected as a Single-ended or a Dual-ended input mode Amplifier. Figure 4 illustrates the different input modes.

In single-ended input operation, one of the inputs is grounded and the signal fed into the other input as shown in Figures 4(a) and 4(b).

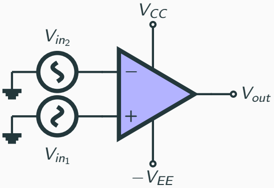
In double-ended or Dual-ended input mode, See Figures 4(c) and 4(d), signals are simultaneously fed into the two input terminals. In this dual-ended input mode, the input configuration maybe tagged Common Mode or Differential Mode depending on the magnitude and phase of the signals fed into the two input terminals.



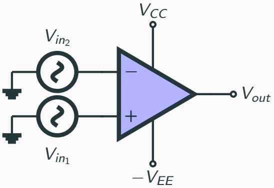
(a) Single ended, inverting mode



(b) Single ended, non-inverting mode



(c) Double ended, differential mode



(d) Double ended, common mode

Figure 4: Op-Amp Input Modes

In the Common Mode, the two signals fed into the input terminals are both same in magnitude and phase as shown in Figure 4(d). In this scenario, the two input signals tends to cancel so that the output is zero. This cancellation action is termed **Common Mode Rejection** and finds significant application in noise cancellation. The ability to reject common mode signal is a measure of an amplifier performance known as common mode rejection ratio CMRR.

Common Mode Rejection Ratio

The Op-Amp CMRR is the ratio of the deferential mode gain to the common mode gain. It is a measure of the ability of the Op-Amp to suppress signals common to the two inputs.

Need for Feedback in Op-Amps

With Op-Amp the amount of amplification is determined entirely by the Op-Amp's internal open-loop gain. This dependence on the open-loop gain is not desirable for the following reasons:

1. as a design engineer, you will want to have control on your system gain by means of external circuitry; and
2. the open loop gain A_V is so high that the system will easily be driven deep into the saturation region or its limit for any small differential input voltage.

To resolve this, the concept of negative feedback is introduced. A negative feedback is a self-regulatory mechanism in which part of the output signal is fed back into the input so as to curtail the changes in the output.

The goal of the negative feedback is to keep the Op-Amp in the linear region, this is achieved by the following;

1. reduce the differential voltage V_d at the input to the barest minimum,
2. reduce the effective gain of the Op-Amp such that the output does not depend on the open-loop gain.

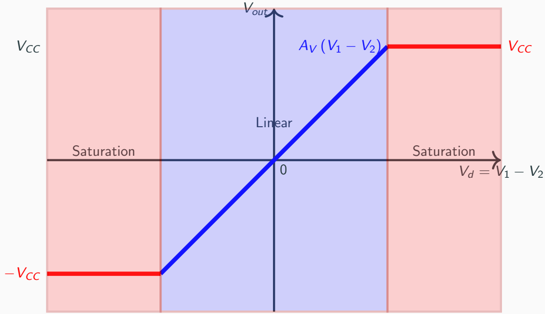


Figure 5: Voltage Transfer Characteristics

Let us consider the negative feedback network arrangement of Figure 6.

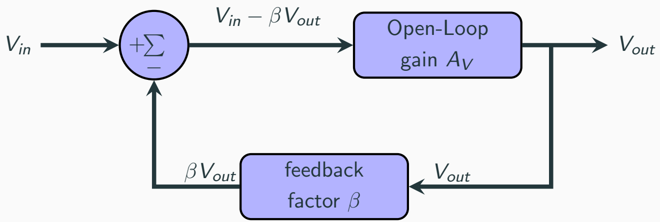


Figure 6: Functional Block Diagram of Feedback System

The close loop gain can be obtained from the functional block diagram as

$$A_{v_c} = \frac{A_v}{1 + \beta A_v} \tag{2}$$

Effects of Negative Feedback

The effects of negative feedback is as follow:

1. Forces the system to operate in the linear region thus reducing the effect of device non-linearity as well as stabilizing the gain. Consequently distortions such as total harmonic distortion are reduced;
2. Increases the bandwidth of the system;
3. Increases the input impedance as well as reduces the output impedance.
4. A reduction in gain.

Effects of Negative Feedback

To conclude on the effect of negative feedback, lets take a look at the Bode plot of Figure 7. We immediately see the effect of reducing the gain as it results to increase in the bandwidth. The reduction in gain is known as the **sacrifice factor**, which is the difference between the close loop gain and the open loop gain.

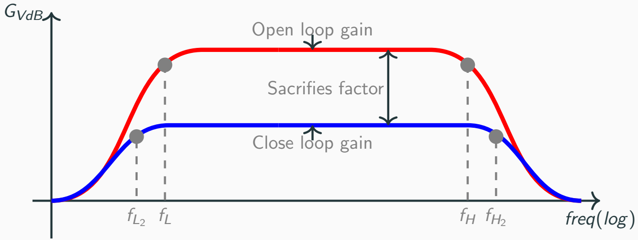
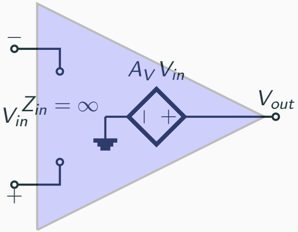
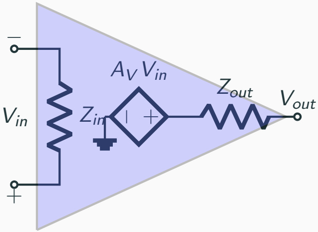


Figure 7: Gain Vs Frequency Response with and without Feedback

The Op-Amp representation is shown in Figure 8. The ideal Op-Amp is shown in Figure 8(a) and the practical Op-Amp in Figure 8(b) for contrast purpose.



(a) Ideal Op-Amp



(b) Practical Op-Amp

Figure 8: Basic Op-Amp Representation

Practical Op-Amp

We can state the following facts about the practical Op-Amp from the discussion thus far;

1. The Op-Amp circuit with feedback operates by maintaining a tiny differential voltage V_d at its inputs to tame the Op-Amp's huge internal/open loop gain;
2. The Op-Amp with feedback regulates its own differential voltage by adjusting its output voltage V_{out}, whose fraction is feed back to the input through the feedback loop; and
3. As the open loop gain A_v is increased, the input differential voltage V_d moves closer to zero. That is $V_1 \approx V_2$.

Ideal Op-Amp

We can state the following facts about the ideal Op-Amp from the discussion thus far;

1. Infinite open-loop gain $A_V = \infty$;
2. Infinite input resistance $Z_{in} = \infty$ and so zero input currents, $I_1 = I_2 = 0$;
3. Zero output resistance $Z_{out} = 0$;
4. Infinite bandwidth with zero phase shift and slew rate[1]; and
5. Infinite common-mode refection ratio (CMRR).

[1] Slew rate will be defined in later section

Ideal Op-Amp golden rules

Let us emphasis the golden rules of the ideal Op-Amp that shall be of great importance in subsequent circuit analysis of the Op-Amp.

1. The differential voltage is zero so that $V_1 = V_2$ in a closed loop or better stated, with the feedback configuration.
2. The Op-Amp's inputs draw no current given input impedance is infinity, so that currents into the Op-Amp internal circuitry through the two input pins 1 and 2 are zero. That is, $I_1 = I_2 = 0$.

Non-inverting Op-Amp

The name Non-inverting is because the input signal is fed into the non-inverting terminal, that is, the negative terminal. Equation 3 is the close-loop gain for a non-inverting Op-Amp.

$$\therefore A_{v_c} = 1 + \frac{R_F}{R_1} \tag{3}$$

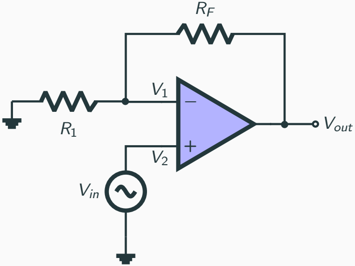


Figure 9: Non-Inverting Op-Amp

Inverting Op-Amp

This configuration is known as the inverting Op-Amp configuration because the input signal is feed into the inverting terminal, V_1. Equation 4 is the close-loop gain for the inverting amplifier.

$$\therefore A_{v_c} = -\frac{R_F}{R_{in}} \tag{4}$$

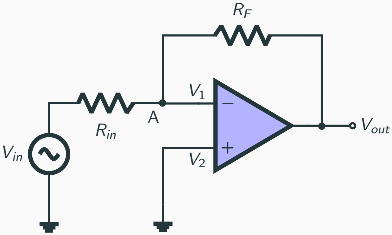


Figure 10: Inverting Op-Amp

Buffer Op-Amp

It is also known as the unity follower or voltage follower. The buffer is a non-inverting amplifier without a feedback resistor.

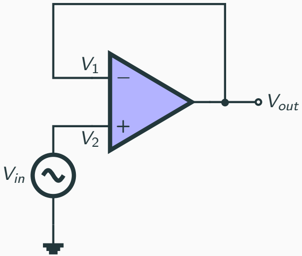


Figure 11: Buffer Amplifier

The close loop gain is

$$A_{V_c} = \frac{V_{out}}{V_1} = 1 \tag{5}$$

Summer Amplifier

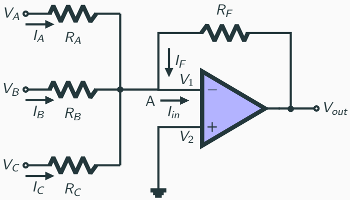


Figure 12: Summer Amplifier

The output voltage is

$$V_{out} = -\frac{R_F}{R_A} V_A - \frac{R_F}{R_B} V_B - \frac{R_F}{R_C} V_C \tag{6}$$

If we set $R_i = R_A = R_B = R_C$, then

$$V_{out} = -\frac{R_F}{R_i} (V_A + V_B + V_C) \tag{7}$$

The DAC transforms digital signal to analogue signal. It is actually a weighted summing amplifier.

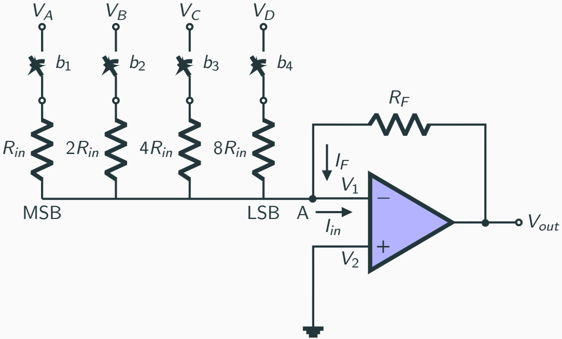


Figure 13: DAC: Digital to Analogue Converter

Subtractor

The Subtractor also known as the Difference Amplifier, amplifies the difference between two inputs while rejecting common signal to the two inputs.

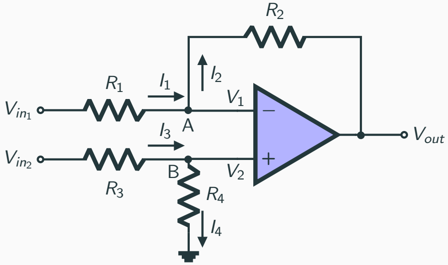


Figure 14: Difference Amplifier

The output voltage is given as

$$V_{out} = \frac{R_2\left(1 + {}^{R_1}/_{R_2}\right)}{R_1\left(1 + {}^{R_3}/_{R_4}\right)} V_{in_2} - \frac{R_2}{R_1} V_{in_1} \tag{8}$$

for our difference amplifier, we wish that common signals be cancelled, that is $V_{out} = 0$, to obtain this, we need to set $R_1 = R_3$ and $R_2 = R_4$, so that equation 8 becomes

$$V_{out} = \frac{R_2}{R_1}\left(V_{in_2} - V_{in_1}\right) \tag{9}$$

Integrator Circuit

The integrator circuit is an inverting amplifier with a capacitor replacing the feedback resistor. The output voltage is

$$V_{out} = -\frac{1}{R_{in} C_F} \int V_{in} dt + K \tag{10}$$

where K is the constant of integration.

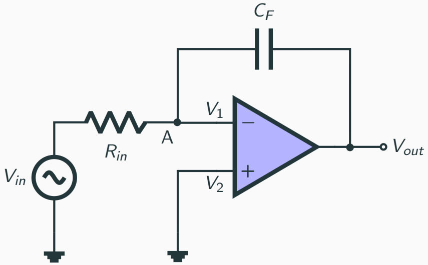


Figure 15: Integrator

Differentiator Circuit

This configuration is an inverting amplifier as with the integrator, however the input resistor R_{in} is replaced by an input capacitor, C_{in}. The output voltage is

$$V_{out} = -R_F C_{in} \frac{dV_{in}}{dt} \tag{11}$$

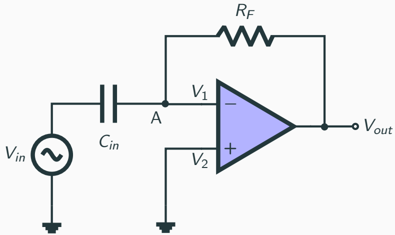


Figure 16: Differentiator Circuit

Instrumentation Amplifier

The instrumentation amplifier is a special and versatile extension of difference amplifiers. It is used for precision measurement and process control. It uses Op-Amp in such way as to amplify small difference in input voltages. Typical application includes isolation amplifiers, thermocouple amplifiers and data acquisition systems. Figure 17 is the circuit implementation of the instrumentation amplifier, it consists of three Op-Amps and seven resistors. The resistor R_4 is typically an external resistor and serve for gain modulation or control as the user can change the value to suit design purposes. The output voltage of the Instrumentation Amplifier is

$$V_{out} = \frac{R_2}{R_1}\left(1 + \frac{2R_3}{R_4}\right)(V_{in_2} - V_{in_1}) \tag{12}$$

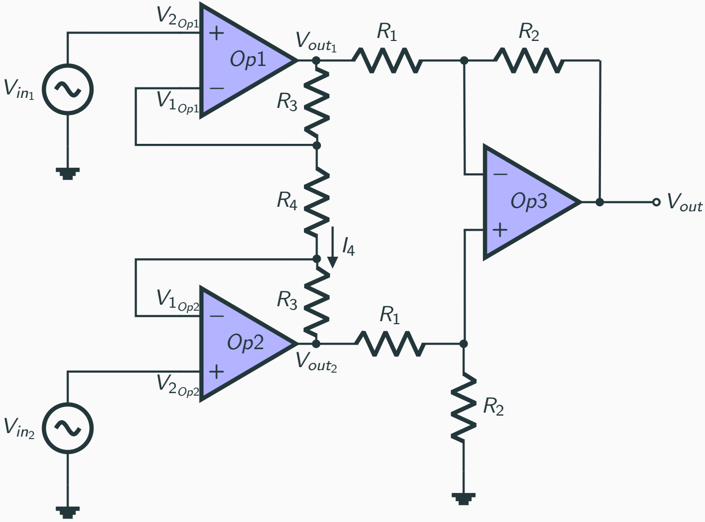


Figure 17: Instrumentation Amplifier

Logarithm Amplifier

A logarithm amplifier is an inverting Op-Amp circuit that produces an output that is proportional to the logarithm of the applied input. The output is given as

$$V_{out} = -nV_T \ln\left(\frac{V_{in}}{R_{in} I_S}\right) \tag{13}$$

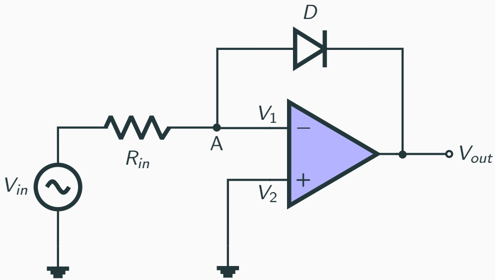


Figure 18: Logarithm Amplifier

Anti-Logarithm Amplifier

An anti-logarithm or exponential amplifier is an inverting Op-Amp circuit that produces an output that is proportional to the anti-logarithm of the applied input voltage. The output is given as

$$V_{out} = -R_F I_S exp^{V_{in}/nV_T} \tag{14}$$

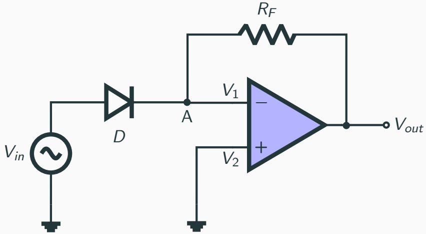


Figure 19: Anti-Logarithm Amplifier

Comparator

The Comparator is an open loop configuration that operates in the saturation region of the transfer characteristic plot of Figure 5. The open-loop Op-Amp Comparator behaves like a digital bistable device because it has two output states. The Comparator, can be termed inverting or non-inverting depending on the pin the **input voltage** is applied. Figure 20 is a non-inverting Comparator with a DC reference voltage V_{ref}.

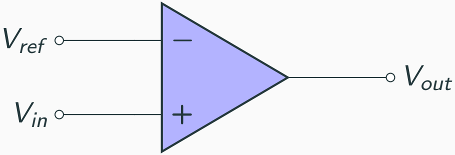


Figure 20: Comparator

Figure 21 describes the operation of the Comparator. The output is such that whenever $V_{in} > V_{ref}$ then the differential voltage $V_d = V_{in} - V_{ref}$ is positive so that the output swings to V_{CC}. However, if $V_{in} < V_{ref}$, the output switches to $-V_{EE}$.

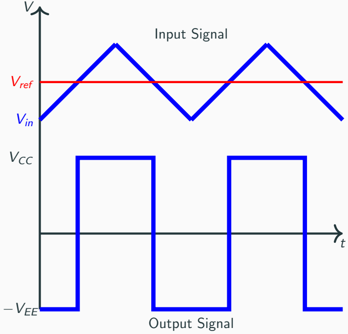


Figure 21: Non-inverting Comparator

Schmidt Trigger

The Schmidt Trigger is a Comparator circuit but with a positive feedback and used to convert any regular or irregular shaped input waveform into a square wave output voltage or pulse.

The Schmidt Trigger is an improved Comparator with two reference voltages (hysteresis), as such offers noise immunity. With the comparator, a noisy signal could create a *ping-pong* effect particularly if the noisy input voltage is around the one reference voltage. However, with the introduction of a second reference voltage a buffer region or hysteresis width is created.