Analog Electronics

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Operational Amplifier

An **operational amplifier** (*OP-Amp*) *is a circuit that can perform such mathematical operations as addition, subtraction, integration and differentiation.*

Properties of Operational Amplifier

- An operational amplifier is a multistage amplifier. The input stage of an *OP*-amp is a differential amplifier stage.
- An inverting input and a non-inverting input.
- A high input impedance at both inputs.
- A low output impedance (< 200 Ω).
- A large open-loop voltage gain, typically 105.
- The voltage gain remains constant over a wide frequency range.
- Very large *CMRR* (> 90 dB).

Differential Amplifier (DA)

A **differential amplifier** *is a circuit that can accept two input signals and amplify the difference between these two input signals.*

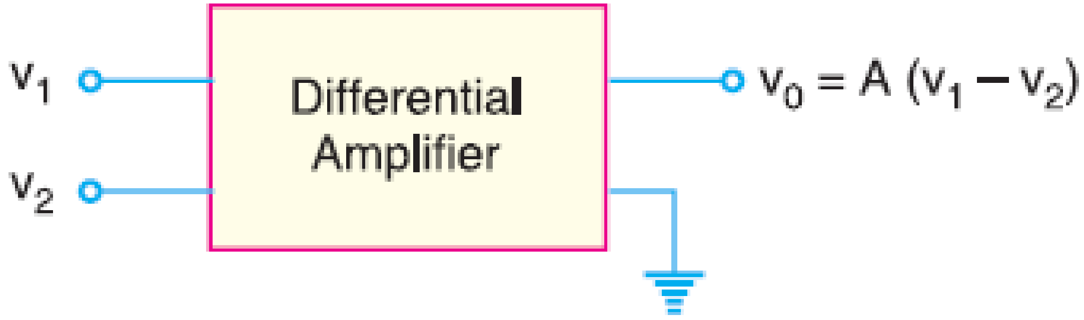


Fig. 4.1

Fig. 4.1 shows the block diagram of a differential amplifier. There are two input voltages v_1 and v_2. This amplifier amplifies the difference between the two input voltages.

- Therefore, the output voltage is $V_0 = A(v_1 - v_2)$ where A is the voltage gain of the amplifier.

Differential Amplifier (DA)

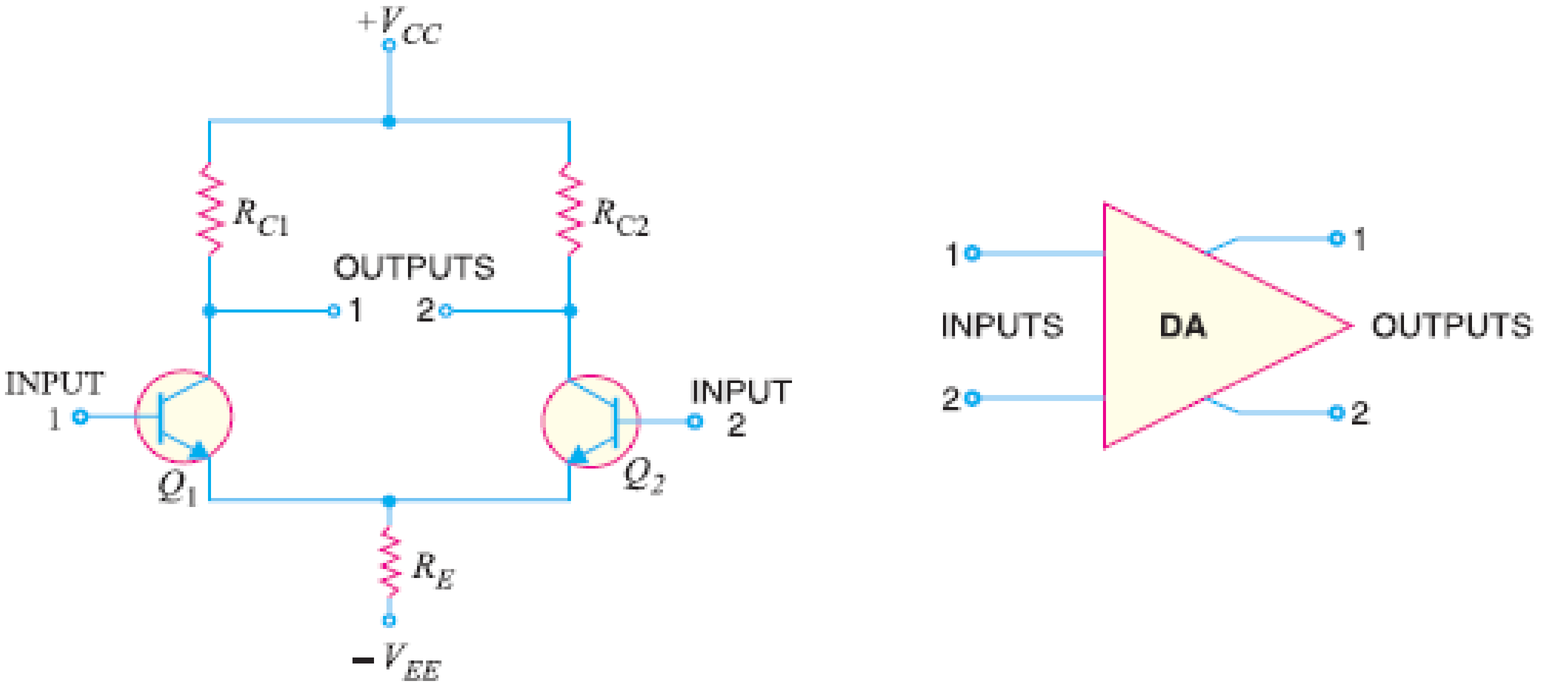


Fig 4.2 Basic circuit of a differential amplifier

- The differential amplifier (*DA*) is a two-input terminal device using at least two transistors.
- There are two output terminals marked 1 (v_{out1}) and 2(v_{out2}).
- The *DA* transistors Q_1 and Q_2 are matched so that their characteristics are the same.
- The collector resistors (R_{C1} and R_{C2}) are also equal.
- The equality of the matched circuit components makes the *DA* circuit arrangement completely symmetrical.

Differential Amplifier (DA)

The *DA* transistors Q_1 and Q_2 are matched so that their characteristics are the same. The collector resistors (R_{C1} and R_{C2}) are also equal. The equality of the matched circuit components makes the *DA* circuit arrangement completely symmetrical.

We can apply signal to a differential amplifier (*DA*) in the following two ways :

(*a*) The signal is applied to one input of *DA* and the other input is grounded. In that case, it is called *single-ended input* arrangement.

(*b*) The signals are applied to both inputs of *DA*. In that case, it is called *dual-ended* or *double-ended input* arrangement.

We can take output from *DA* in the following two ways :

(*a*) The output can be taken from one of the output terminals and the ground. In that case, it is called *single-ended output* arrangement.

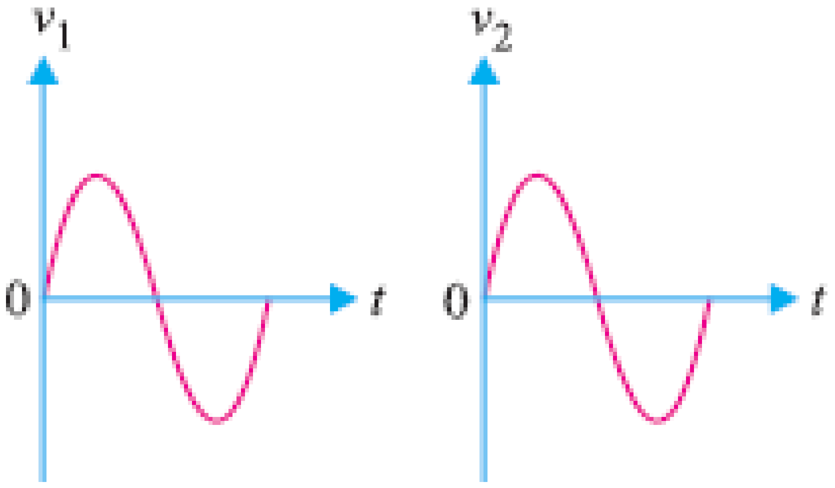
(*b*) The output can be taken between the two output terminals (*i.e.*, between the collectors of Q_1 and Q_2). In that case, it is called *double-ended output* arrangement or *differential output.*

Generally, the differential amplifier (DA) is operated for single-ended output. In other words, we take the output either from output terminal 1 and ground or from output terminal 2 and ground. Any input/output terminal that is grounded is at *0V*.

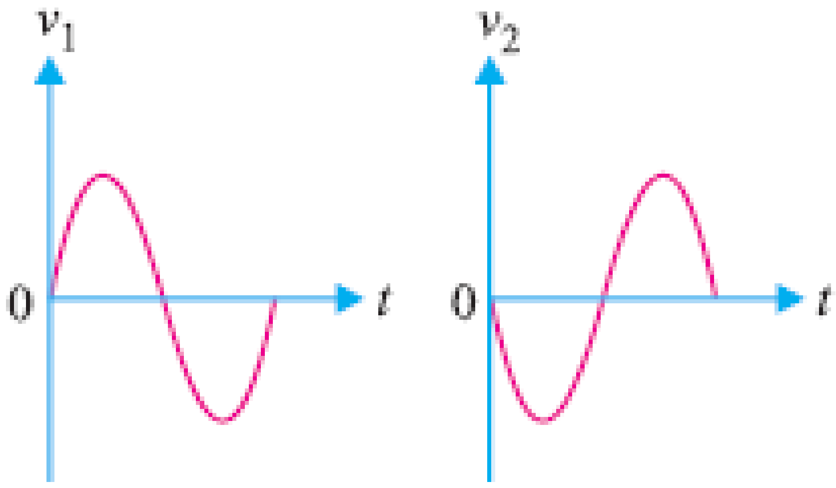
Differential Amplifier (DA)

<u>Common-mode signals</u>: When the input signals to a *DA* are in phase and exactly equal in amplitude, they are called *common-mode signals*.

<u>Differential-mode signals</u>. When the input signals to a *DA* are 180° out of phase and exactly equal in amplitude, they are called *differential-mode signals*.



Common-mode signals



Differential-mode signals

Common-mode Rejection Ratio (CMRR)

A differential amplifier should have high differential voltage gain (A_{DM}) and very low common-mode voltage gain (A_{CM}). The ratio A_{DM}/A_{CM} is called common-mode rejection ratio ($CMRR$) *i.e.*,

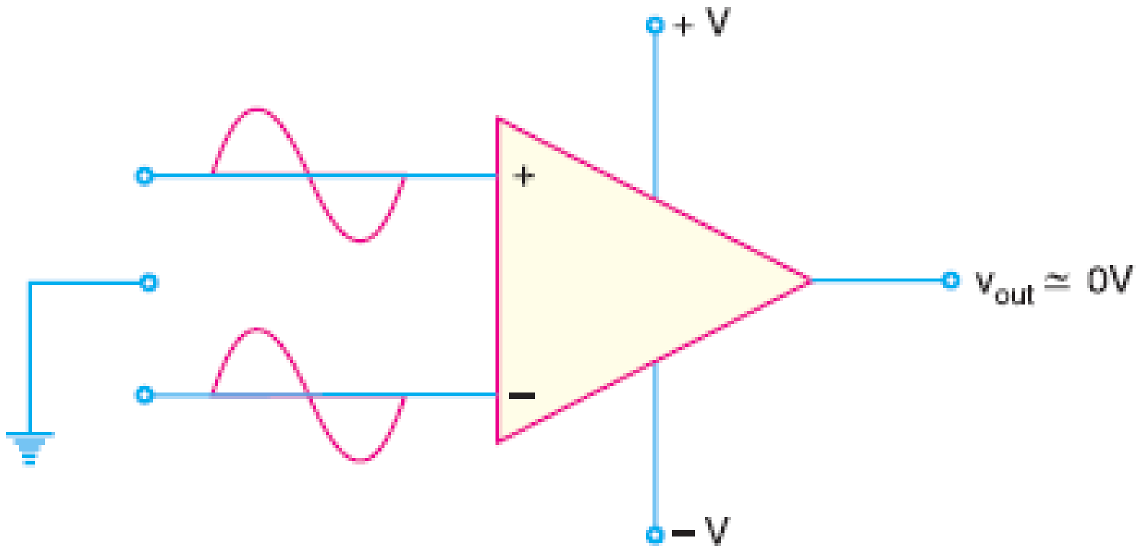
$$CMRR = \frac{A_{DM}}{A_{CM}}$$

Very often, the $CMRR$ is expressed in decibels (dB). The decibel measure for $CMRR$ is given by;

$$CMRR_{dB} = 20\log_{10}\frac{A_{DM}}{A_{CM}} = 20\log_{10}CMRR$$

Common-mode Rejection Ratio (CMRR)

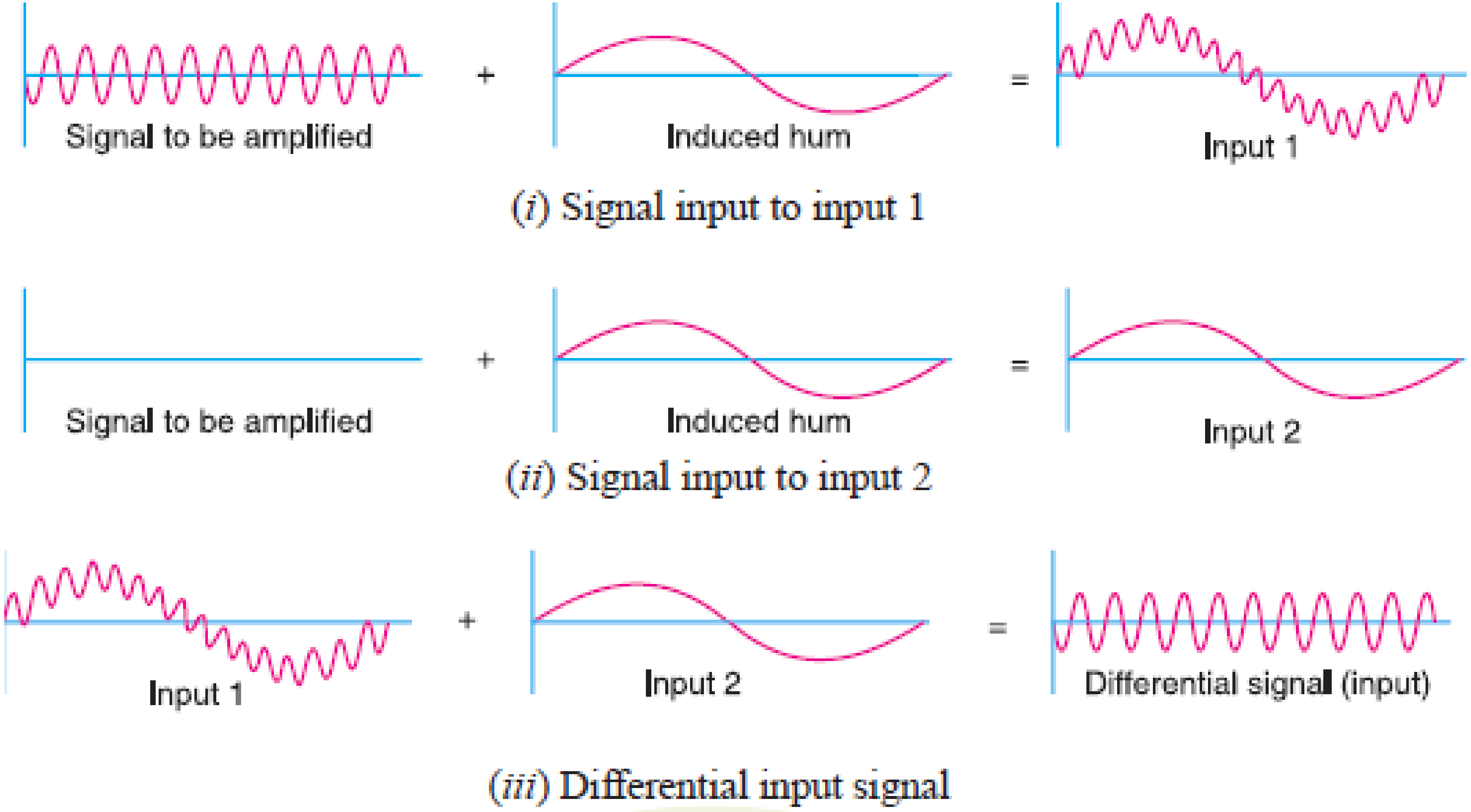
Importance of CMRR: The *CMRR* is the ability of a *DA* to reject the common-mode signals. The larger the *CMRR*, the better the *DA* is at eliminating common-mode signals. Common mode signals are usually *undesired signals* caused by external interference. For example, any *RF* signals picked up by the *DA* inputs would be considered undesirable. The *CMRR* indicates the *DA*'s ability to reject such unwanted signals.



Common-mode Rejection Ratio (CMRR)

- How does a differential amplifier reject hum and static voltages induced into its input leads???

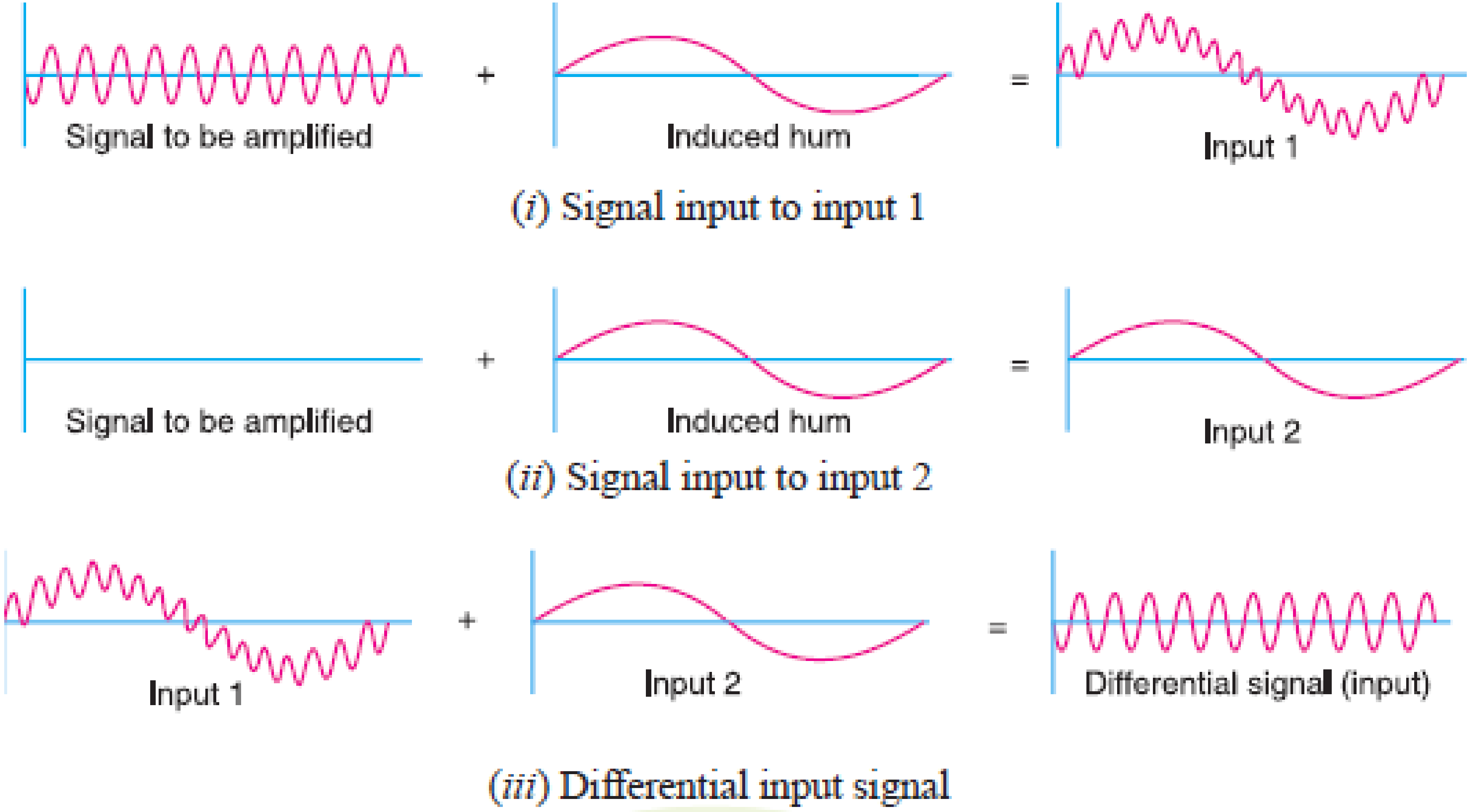
Common-mode Rejection Ratio (CMRR)



In Fig. 4.5, the signal is applied to input 1 of the *DA*. However, a low frequency *hum* voltage is also induced into the lead wire. The resultant waveform is shown in Fig. 4.5 (*i*).

However, a *DA* also has second input (input 2). Therefore, the lead of second input has the same phase 50 Hz hum induced into it. This is the only voltage (*i.e.*, hum) applied to input 2 as shown in Fig. 4.5 (*ii*).

Common-mode Rejection Ratio (CMRR)



As shown in Fig. 4.5 (*iii*), the hum components of the two inputs form a common-mode signal which is largely rejected by the *DA*. If the input hum signals are equal at the input, then differential input to *DA* will be devoid of hum. Therefore, the amplified output of *DA* will be free from the hum.

Example 25.2. *A certain differential amplifier has a differential voltage gain of 2000 and a common mode gain of 0.2. Determine CMRR and express it in dB.*

Example 25.3. *A differential amplifier has an output of 1V with a differential input of 10 mV and an output of 5 mV with a common-mode input of 10 mV. Find the CMRR in dB.*

Common-mode Rejection Ratio (CMRR)

Example 25.2. *A certain differential amplifier has a differential voltage gain of 2000 and a common mode gain of 0.2. Determine CMRR and express it in dB.*

Solution.

$$CMRR = \frac{A_{DM}}{A_{CM}} = \frac{2000}{0.2} = \mathbf{10{,}000}$$

$$CMRR_{dB} = 20 \log_{10} 10{,}000 = \mathbf{80dB}$$

Example 25.3. *A differential amplifier has an output of 1V with a differential input of 10 mV and an output of 5 mV with a common-mode input of 10 mV. Find the CMRR in dB.*

Solution. Differential gain, $A_{DM} = 1\text{V}/10\text{ mV} = 100$

Common-mode gain, $A_{CM} = 5\text{ mV}/10\text{ mV} = 0.5$

$$\therefore \quad CMRR_{dB} = 20 \log_{10} (100/0.5) = \mathbf{46\ dB}$$

Example 25.4. *A differential amplifier has a voltage gain of 150 and a CMRR of 90 dB. The input signals are 50 mV and 100 mV with 1 mV of noise on each input. Find* (*i*) *the output signal* (*ii*) *the noise on the output.*

Common-mode Rejection Ratio (CMRR)

Example 25.4. *A differential amplifier has a voltage gain of 150 and a CMRR of 90 dB. The input signals are 50 mV and 100 mV with 1 mV of noise on each input. Find (i) the output signal (ii) the noise on the output.*

Solution.

(*i*) Output signal, $v_{out} = A_{DM}(v_1 - v_2) = 150\ (100\ \text{mV} - 50\ \text{mV}) = \mathbf{7.5\ V}$

(*ii*) $CMRR_{dB} = 20 \log_{10} (150/A_{CM})$

or $90 = 20 \log_{10} (150/A_{CM})$

$\therefore\ A_{CM} = 4.7 \times 10^{-3}$

Noise on output $= A_{CM} \times 1\ \text{mV} = 4.7 \times 10^{-3} \times 1\text{mV} = \mathbf{4.7 \times 10^{-6}\ V}$

Slew Rate

The slew rate of an *OP*-amp is a measure of *how fast the output voltage can change* and is measured in volts per microsecond (V/μs). If the slew rate of an *OP*-amp is 0.5V/μs, it means that the output from the amplifier can change by 0.5 V every μs. Since frequency is a function of time, the *slew rate can be used to determine the maximum operating frequency of the OP-amp* as follows:

$$\text{Maximum operating frequency, } f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}}$$

Here V_{pk} is the peak output voltage.

Problem

What is the maximum operating frequency of an amplifier having an input signal to a peak output voltage of 100 mV and slew rate of 0.5 V/μs.

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The maximum operating frequency (f_{max}) of the amplifier is given by;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\,V/\mu s}{2\pi \times 0.1} \qquad (\because\ 100\text{ mV} = 0.1\text{V})$$

$$= \frac{500\text{ kHz}}{2\pi \times 0.1} = \mathbf{796\ kHz} \qquad (\because\ 0.5\text{V}/\mu\text{s} = 500\text{ kHz})$$