

Operational Amplifier

Signal Gain versus Noise Gain and Input Referred Errors

Abstract

This document discusses the signal gain and noise gain for the non-inverting and inverting amplifier configurations and explains the various input referred error voltages.

Contents

1.	Signal Gain and Noise Gain of the Non-inverting Amplifier	2
2.	Signal Gain and Noise Gain of the Inverting Amplifier	2
3.	Input Referred Errors.....	3
4.	Input Offset Voltage (V_{OS})	3
5.	Input Bias Current (I_B).....	4
6.	Finite Open-Loop Gain (A_{OL})	6
7.	Common-Mode Rejection Ratio (CMRR)	6
8.	Power-Supply Rejection Ratio (PSRR)	8
9.	Conclusion	8
10.	Revision History.....	8

List of Figures

Figure 1.	Non-inverting Amplifier Model	2
Figure 2.	Non-inverting Amplifier with Error Voltage	2
Figure 3.	Inverting Amplifier Model	2
Figure 4.	Inverting Amplifier with Error Voltage	2
Figure 5.	Mismatch in Transistor Parameters Causes V_{OS}	3
Figure 6.	Grounding Both Inputs Still Produces V_{OS}	3
Figure 7.	Adjusting V_{EXT} until $V_O = 0V$ Makes $V_{EXT} = -V_{OS}$	3
Figure 8.	V_{OS} Model of Practical Op-amp	3
Figure 9.	Input Stage with I_{B+} and I_{B-}	4
Figure 10.	Uncompensated Error Due to I_{B-} Flowing through R_F and R_G	4
Figure 11.	Compensated Error Due to R_P Reducing the Potential at v_p	4
Figure 12.	Uncompensated Case of the Non-inverting Amplifier	5
Figure 13.	Compensated Case of the Non-inverting Amplifier	5
Figure 14.	Uncompensated Case of the Inverting Amplifier	5
Figure 15.	Compensated Case of the Inverting Amplifier	5
Figure 16.	Input Error Due to Finite A_{OL}	6
Figure 17.	Changes in VCM Cause Changes in V_O	6
Figure 18.	VCM Alters Operating Points of Q1 and Q2.....	6
Figure 19.	Op-amp Transfer Characteristic with VCM.....	6
Figure 20.	CMRR over Frequency	7
Figure 21.	Non-inverting Amplifier with Common-mode Error: $E_I = V_I / CMRR$	7
Figure 22.	Inverting Amplifier with no Common-mode Error	7
Figure 23.	Changes in V_S Cause Changes in V_O	8
Figure 24.	ΔV_S Alters Operating Points of Q1 and Q2	8
Figure 25.	Input Error Due to Supply Changes, ΔV_S	8
Figure 26.	PSRR over Frequency	8

1. Signal Gain and Noise Gain of the Non-inverting Amplifier

The standard form of the amplifier output voltage, $V_O = V_I \frac{A_{OL}}{1 + A_{OL} \beta}$ derived in TB514, Operational Amplifier Basics,

does not reveal by how much the amplifier's differential input voltage, V_{id} , is amplified towards the output.

However, this input voltage is the sum of all input referred error voltages, which are due to noise, finite open-loop gain, or common-mode and power-supply rejection. Therefore, it is good to know how much output error to expect that is due to the input referred errors being amplified by the circuit gain.

[Figure 1](#) shows the model for the non-inverting amplifier. The following loop equation shows the input voltage as the sum of the feedback and the differential input voltage, $V_I = V_{id} + V_O$. Then solving for V_O gives:

$$(EQ. 1) \quad V_O = \frac{1}{\beta} V_I - \frac{1}{\beta} V_{id} = \frac{1}{\beta} (V_I - V_{id})$$

This shows that for the non-inverting amplifier, the signal input and the differential input are equally amplified by the circuit gain, $1/\beta$, with V_{id} having the opposite polarity of V_I . Presenting V_{id} as an input error, E_I , then leads to the circuit diagram in [Figure 2](#).

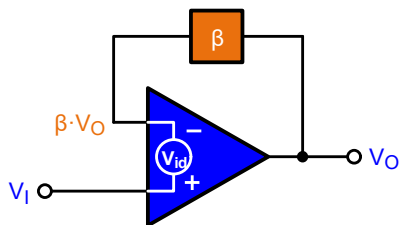


Figure 1. Non-inverting Amplifier Model

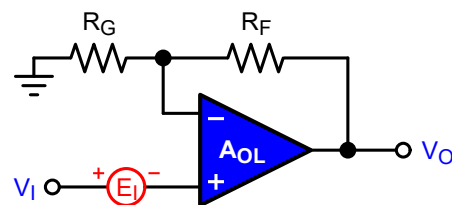


Figure 2. Non-inverting Amplifier with Error Voltage

2. Signal Gain and Noise Gain of the Inverting Amplifier

For the inverting amplifier configuration, the voltage at the inverting op-amp input is the sum of the signal input voltage attenuated by $\alpha = R_F / (R_G + R_F)$ and the output voltage attenuated by $\beta = R_G / (R_G + R_F)$. This makes $\alpha = 1 - \beta$.

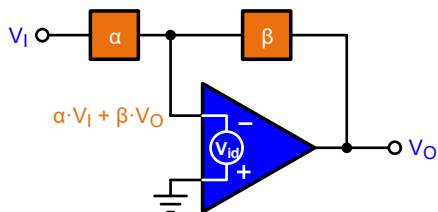


Figure 3. Inverting Amplifier Model

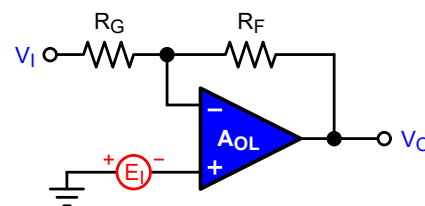


Figure 4. Inverting Amplifier with Error Voltage

Writing the loop equation for the inverting amplifier with $0 = V_{id} + V_I(1 - \beta) + V_O \beta$ and solving for V_O results in:

$$(EQ. 2) \quad V_O = -V_I \left(\frac{1}{\beta} - 1 \right) - \frac{1}{\beta} V_{id}$$

[Equation 2](#) confirms the fact that the signal gain of the inverting amplifier is $1V/V$ less than the $1/\beta$ of the non-inverting amplifier, and the negative sign in front of V_I indicates the 180° phase inversion. However, V_{id} is amplified by the non-inverting gain, $1/\beta$, and therefore assigned to the non-inverting input. Then, replacing V_{id} through E_I results in the circuit diagram in [Figure 4](#).

Comparing [Equation 1](#) and [Equation 2](#) shows that independent of the amplifier configuration, the input error, or input noise, is amplified by the non-inverting gain, $1/\beta$, which is also known as noise gain.

3. Input Referred Errors

As mentioned earlier in this document, the differential input voltage is the sum of all the following:

- Input referred noise or error voltages including the input offset voltage
- Offset voltage due to bias current flowing through the biasing resistors
- Internal noise voltage
- Signal error due to finite open-loop gain
- Input errors due to common-mode and power-supply rejection.

$$V_{id} = V_{OS} + I_{B+} \cdot R_S - I_{B-} \cdot R_S + V_n + \frac{V_O}{A_{OL}} + \frac{\Delta V_{CM}}{CMRR} + \frac{\Delta V_S}{PSRR}$$

4. Input Offset Voltage (V_{OS})

When both op-amp inputs have the same input potential, the output of an ideal op-amp should be 0V. For a practical op-amp (OPA) however, this is usually not the case. Here, the parameter mismatch of the input transistors causes a slight difference in bias voltage (see [Figure 5](#)), making $V_O \neq 0V$ (see [Figure 6](#)). This difference is known as the offset voltage, V_{OS} . To measure V_{OS} , an external voltage (V_{EXT}) is applied to the non-inverting input and adjusted until $V_O = 0V$. At this moment $V_{EXT} = -V_{OS}$ (see [Figure 7](#)).

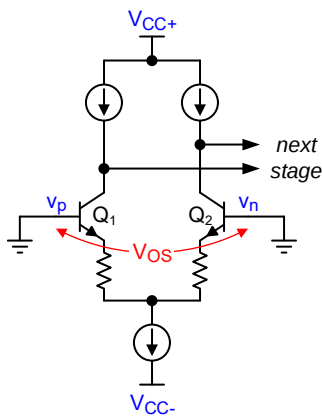


Figure 5. Mismatch in Transistor Parameters Causes V_{OS}

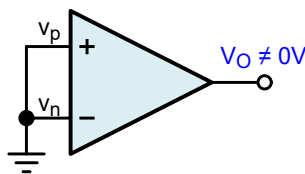


Figure 6. Grounding Both Inputs Still Produces V_O

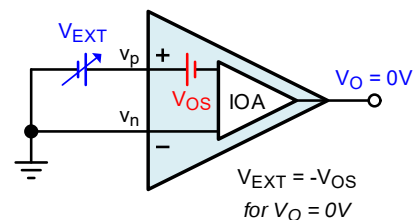


Figure 7. Adjusting V_{EXT} until $V_O = 0V$ Makes $V_{EXT} = -V_{OS}$

Therefore, a practical op-amp can be modeled as an ideal op-amp (IOA) with an offset voltage in series to its non-inverting input (see [Figure 8](#)). The input offset is also known as DC noise.

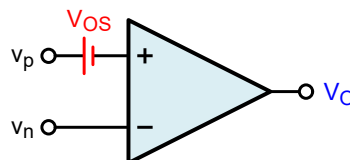


Figure 8. V_{OS} Model of Practical Op-amp

5. Input Bias Current (I_B)

Input bias currents are necessary because they determine the operating point of the input of the op-amp input stage transistors (see [Figure 9](#)). For NPN transistors these currents flow into the device; for PNP transistors they flow out of the device. In fact, both inputs must see a DC current path to ground for the bias currents to flow; otherwise, the op-amp does not work.

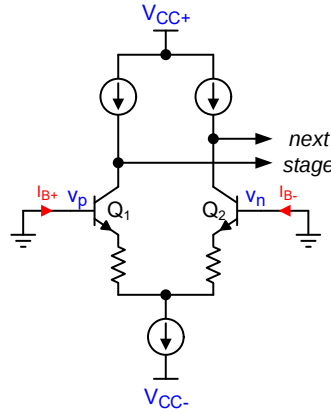


Figure 9. Input Stage with I_{B+} and I_{B-}

Due to the mismatch of the transistor current gains, the bias current into the non-inverting input, I_{B+} , differs from the bias current into the inverting input, I_{B-} . Datasheets usually do not specify the bias currents individually but instead provide an average bias, I_B , and an offset current, I_{OS} . Their definitions are listed in [Equation 3](#) and [Equation 4](#).

$$(EQ. 3) \quad I_B = \frac{I_{B+} + I_{B-}}{2} \quad \text{and} \quad (EQ. 4) \quad I_{OS} = I_{B+} - I_{B-}$$

Note: I_{OS} is usually a magnitude smaller than I_B .

Through mathematical manipulation of [Equation 3](#) and [Equation 4](#), the individual bias currents are identified as:

$$(EQ. 5) \quad I_{B+} = I_B + \frac{I_{OS}}{2} \quad \text{and} \quad (EQ. 6) \quad I_{B-} = I_B - \frac{I_{OS}}{2}$$

The signal error caused by bias currents is due to the voltage drops they cause across the feedback and gain resistors. However, a simple error-compensation technique can be used to minimize this error. The following section discusses the signal error for the uncompensated and compensated case.

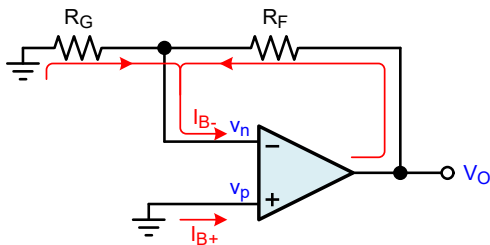


Figure 10. Uncompensated Error Due to I_{B-} Flowing through R_F and R_G

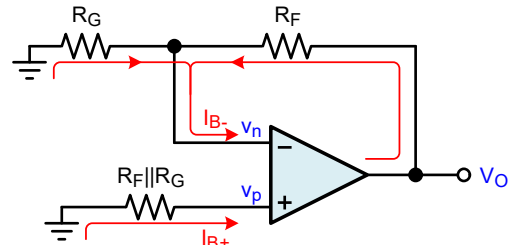


Figure 11. Compensated Error Due to R_P Reducing the Potential at v_p

To determine V_O due to bias current flow, we define I_{B-} as the sum of the two individual currents flowing into the v_n node, and then solve for v_n .

$$I_{B-} = \frac{-v_n}{R_G} + \frac{V_O - v_n}{R_F} \Rightarrow v_n = \frac{V_O}{1 + R_F/R_G} - I_{B-} R_G \parallel R_F$$

Due to op-amp action, $v_n = v_p$, we define v_p for the uncompensated and the compensated case and solve for V_O .

In the uncompensated case $v_p = 0V$, thus:

$$0 = \frac{V_O}{1 + R_F/R_G} - I_{B-} R_G \parallel R_F$$

And solving for V_O gives:

$$V_O = (1 + R_F/R_G) \cdot (R_F \parallel R_G) \cdot I_{B-}$$

Finally substituting I_{B-} with [Equation 6](#) results:

$$V_O = (1 + R_F/R_G) \cdot (R_F \parallel R_G) \cdot (I_B - I_{OS}/2)$$

with the input error, E_I , being:

$$E_I = (R_F \parallel R_G) \cdot (I_B - I_{OS}/2)$$

In the compensated case $v_p = -I_{B+} \cdot (R_F \parallel R_G)$, thus

$$-I_{B+} R_G \parallel R_F = \frac{V_O}{1 + R_F/R_G} - I_{B-} R_G \parallel R_F$$

And solving for V_O gives:

$$V_O = (1 + R_F/R_G) \cdot (R_F \parallel R_G) \cdot (I_{B-} - I_{B+})$$

Finally substituting $-(I_{B+} - I_{B-})$ with [Equation 4](#) results:

$$V_O = (1 + R_F/R_G) \cdot (R_F \parallel R_G) \cdot (-I_{OS})$$

with the input error, E_I , being:

$$E_I = (R_F \parallel R_G) \cdot (-I_{OS})$$

In both cases the input error is amplified by the non-inverting gain and therefore placed in series with the non-inverting input. As both amplifier inputs have been grounded for error analysis, the above models apply equally to the non-inverting and inverting amplifier configurations. [Figure 12](#) to [Figure 15](#) show the respective schematics.

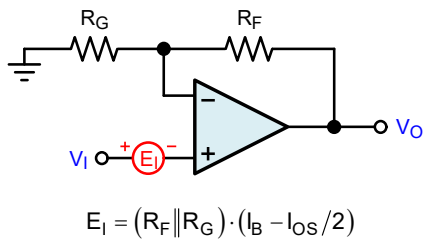


Figure 12. Uncompensated Case of the Non-inverting Amplifier

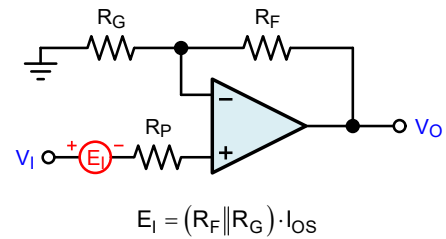


Figure 13. Compensated Case of the Non-inverting Amplifier

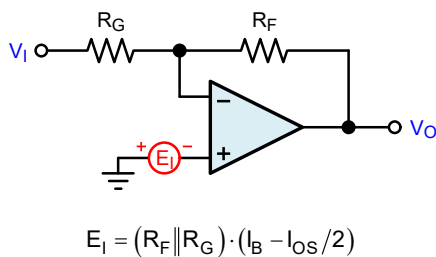


Figure 14. Uncompensated Case of the Inverting Amplifier

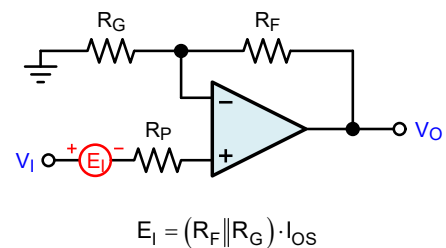


Figure 15. Compensated Case of the Inverting Amplifier

6. Finite Open-Loop Gain (A_{OL})

As already shown in [Figure 1](#) and [Figure 3](#), even a noiseless op-amp requires a minimum differential input, V_{ID-min} , to sustain the desired output voltage. This V_{ID-min} is the ratio of the output voltage divided by the finite open-loop gain, and thereafter, represents an input error in itself: $E_I = V_O/A_{OL}$ (see [Figure 16](#)).

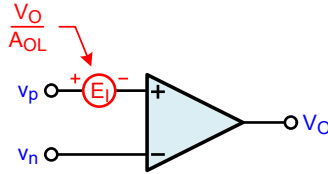


Figure 16. Input Error Due to Finite A_{OL}

Entering this input error into Equations 1 and 2 and solving for V_O/V_I confirms the closed loop gains, $A_{CL(non)}$ and $A_{CL(inv)}$, for the non-inverting and inverting amplifier, respectively.

$$V_O = \frac{1}{\beta} V_I - \frac{1}{\beta} V_{id-min} = \frac{1}{\beta} V_I - \frac{1}{\beta} \cdot \frac{V_O}{A_{OL}} \Rightarrow \frac{V_O}{V_I} = -\left(\frac{1}{\beta} - 1\right) \cdot \frac{1}{1 + \frac{1}{A_{OL}\beta}} = A_{CL(inv)}$$

$$V_O = -V_I \left(\frac{1}{\beta} - 1\right) - \frac{1}{\beta} V_{id} = -V_I \left(\frac{1}{\beta} - 1\right) - \frac{1}{\beta} \cdot \frac{V_O}{A_{OL}} \Rightarrow \frac{V_O}{V_I} = \frac{1}{\beta} \cdot \frac{1}{1 + \frac{1}{A_{OL}\beta}} = A_{CL(nin)}$$

7. Common-Mode Rejection Ratio (CMRR)

In the absence of input offset, an op-amp should respond only to the voltage difference between its inputs, so that $V_O = A_{DM}(v_p - v_n)$. However, a practical op-amp is also somewhat sensitive to changes in the common-mode input voltage (see [Figure 17](#)). This is because a change in V_{CM} changes the operating point of the input transistors (see [Figure 18](#)). The op-amp's transfer characteristic is therefore:

$$(EQ. 7) \quad V_O = A_{DM}(v_p - v_n) + A_{CM} \cdot \Delta V_{CM}$$

where A_{DM} is the differential-mode open-loop gain, A_{OL} , and A_{CM} is the common-mode gain.

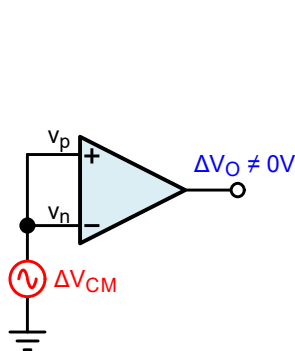


Figure 17. Changes in VCM Cause Changes in V_O

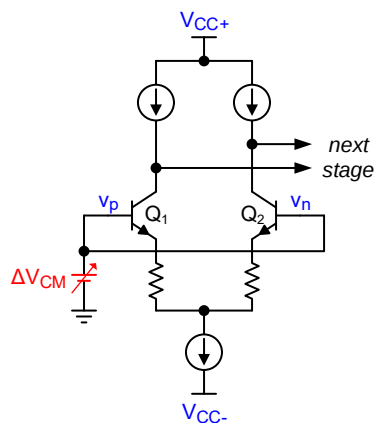


Figure 18. VCM Alters Operating Points of Q1 and Q2

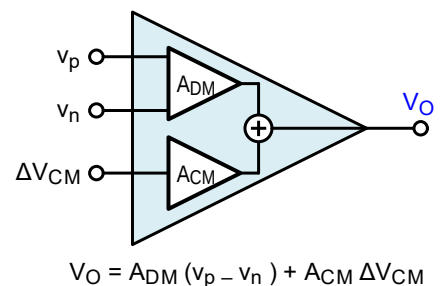


Figure 19. Op-amp Transfer Characteristic with VCM

Because the impact of common-mode voltage is undesired, an op-amp's capability to reject common-mode signals is specified by its common-mode rejection ratio, CMRR, which is the ratio of differential-mode gain to common-mode gain: $CMRR = A_{DM}/A_{CM}$. Using this ratio to express the output voltage, we rewrite Equation 7 in the form: $V_O = A_{DM} [v_p - v_n + (A_{CM}/A_{DM}) \cdot \Delta V_{CM}]$, and substitute the term A_{DM}/A_{CM} through $1/CMRR$, so that:

$$(EQ. 8) \quad V_O = A_{DM} \left(v_p + \frac{\Delta V_{CM}}{CMRR} - v_n \right)$$

Thus, the ratio $\Delta V_{CM}/CMRR$ represents an input error voltage, E_I , that is in series with the non-inverting input, v_p , and therefore amplified with the non-inverting gain: $E_I = \Delta V_{CM}/CMRR$.

The input error due to V_{CM} differs from the input errors due to V_{OS} and I_B in two points:

1. $\Delta V_{CM}/CMRR$ is frequency dependent because CMRR is frequency dependent. At low frequencies, CMRR can reach high values in the range of 80 to 140dB, depending on the type of op-amp. At high frequencies, CMRR rolls off at a rate of 20db/decade (see [Figure 20](#)).

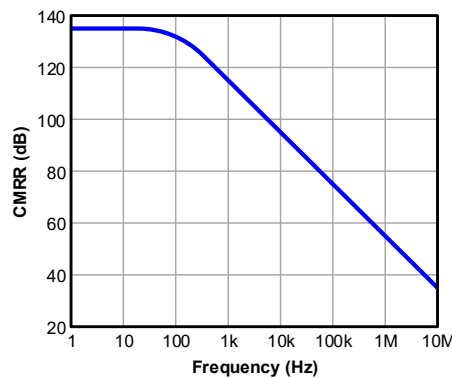


Figure 20. CMRR over Frequency

2. $\Delta V_{CM}/CMRR$ differs between the non-inverting and inverting amplifier configurations due to the difference in ΔV_{CM} between the two.

Because op-amp action ensures that $v_p = v_n$, v_p becomes the common-mode input voltage for the op-amp. For the non-inverting amplifier this means that $\Delta v_p = \Delta v_i = \Delta V_{CM}$ and the input error becomes rather large. However, for the inverting amplifier, v_p is connected to a constant reference potential. This makes $\Delta v_p = \Delta V_{CM} = 0V$ and the input error equals zero. Therefore, applications with large input signal swings can apply the inverting configuration to eliminate common-mode error.

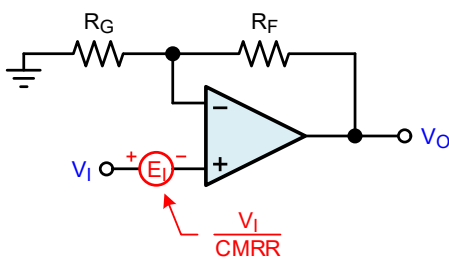


Figure 21. Non-inverting Amplifier with Common-mode Error: $E_I = V_I / CMRR$

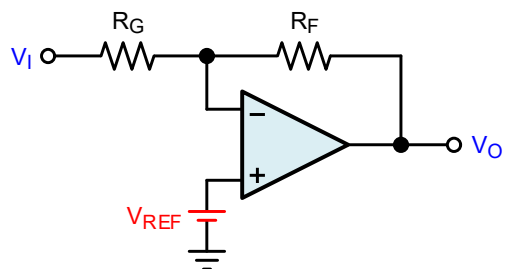


Figure 22. Inverting Amplifier with no Common-mode Error

8. Power-Supply Rejection Ratio (PSRR)

Like the common-mode phenomenon, changes in the op-amp the power supply causes changes in the output voltage (see [Figure 23](#)). This is because a change in V_S alters the operating point of the input transistors (see [Figure 24](#)). An op-amp's capability to reject supply changes is expressed through its power supply rejection ratio, or PSRR (see [Figure 25](#)).

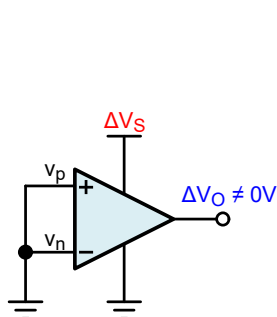


Figure 23. Changes in V_S Cause Changes in V_O

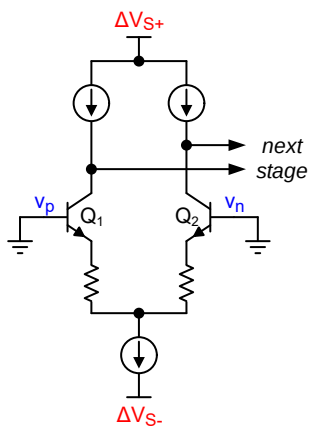


Figure 24. ΔV_S Alters Operating Points of Q_1 and Q_2

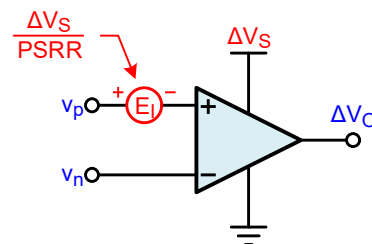


Figure 25. Input Error Due to Supply Changes, ΔV_S

In analogy to the CMRR, the PSRR can be modeled as an input error, $E_I = \Delta V_S / \text{PSRR}$, which is in series with the non-inverting input and is amplified with the non-inverting gain (see [Figure 25](#)). Like CMRR, the PSRR is frequency dependent with high values at low frequencies and a 20dB/decade roll-off at high frequencies (see [Figure 26](#)).

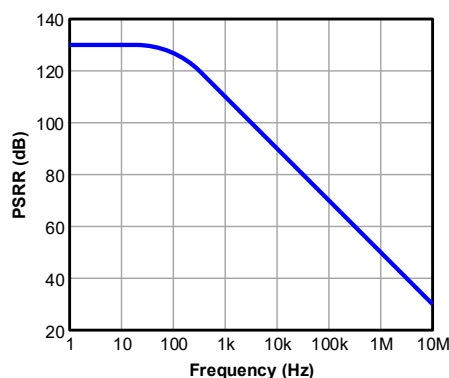


Figure 26. PSRR over Frequency

Unlike the input error due to CMRR, the input error due to PSRR affects the non-inverting and inverting amplifier configurations equally.

9. Conclusion

The op-amp input referred errors can be modeled as input error voltages assigned to the non-inverting op-amp input. Apart from the CMRR induced error, all other error voltages are amplified by the non-inverting gain (such as noise gain, independent of the amplifier configuration). The CMRR induced error, $\Delta V_{CM} / \text{CMRR}$, does not exist in the inverting amplifier; it is only present in the non-inverting amplifier.

10. Revision History

Rev.	Date	Description
1.00	Oct 2.19	Initial release

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