Application Note

Optimizing CMRR in Differential Amplifier Circuits With Precision Matched Resistor Divider Pairs

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ABSTRACT

Differential signals rely on the high common-mode rejection of differential amplifier circuits to reduce noise and other errors. This application note explores the relationship between resistor tolerance and common-mode rejection in difference amplifier circuits. Equations are derived to determine the common-mode rejection ratio (CMRR) of a differential amplifier circuit as a function of absolute resistance, resistor tolerance, or matched ratio tolerance. The precision ratiometric matching of the RES11A-Q1 thin-film resistor divider pair can improve the effective CMRR of a difference amplifier circuit.

Table of Contents

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1 Introduction to Differential Signaling

A differential voltage signal is defined as the difference in voltage between two signal-carrying traces. Often these signals are balanced, meaning that the two signal voltages are equal in magnitude but of opposite polarity, as shown in Figure 1-1. The differential voltage (V_{Diff}) can be resolved by subtracting the positive signal voltage from the negative signal voltage as shown in Equation 1.

$$V_{Diff} = V_{Sig+} - V_{Sig-} \tag{1}$$

This subtraction function is one of the main benefits of differential signaling, as the subtraction function removes unwanted common-mode voltages from the signal chain. A common-mode voltage (V_{CM}) is a voltage that is present on both signal traces, that is equal in both magnitude and polarity. In differential circuits, V_{CM} is defined as the average of the two signal voltages, Equation 2.

$$V_{CM} = \frac{V_{Sig+} + V_{Sig-}}{2} \tag{2}$$

These unwanted common-mode voltages can be in the form of noise, or as a DC bias from the previous signal stage. Unlike the signal voltages which are of opposite polarity, these common-mode voltages are rejected by the subtraction function defined in Equation 1. The following figures illustrate this principle for both AC and DC common-mode voltages.

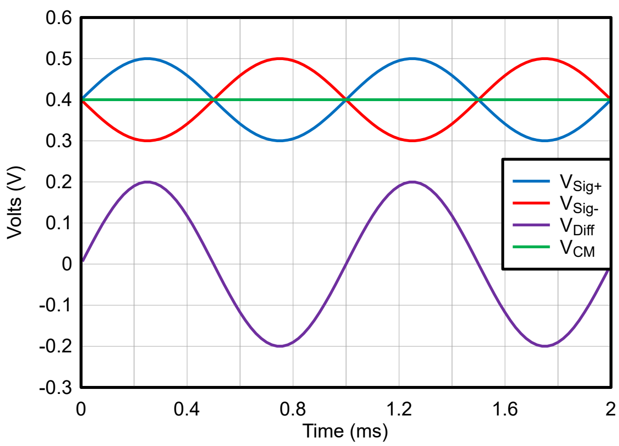

Figure 1-1. AC Differential Signal with DC Common-Mode Voltage

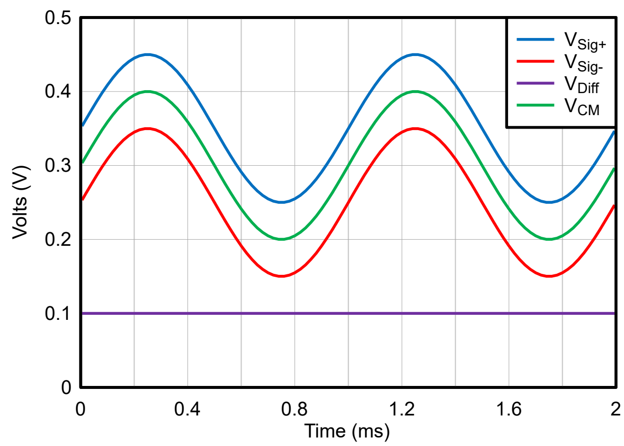

Figure 1-2. DC Differential Signal with AC Common-Mode Voltage

In practical electrical circuits the common-mode voltage is not perfectly removed from the differential signal, however it can be significantly attenuated. The magnitude of the common-mode attenuation is determined by various non-idealities in the circuit, as discussed in the following sections.

2 Common-Mode Rejection Ratio in Difference Amplifier Circuits

Difference amplifiers, often referred to as *diff-amps*, are designed to convert a differential input voltage into a single-ended output voltage as a real world implementation of Equation 1. Figure 2-1 illustrates a typical difference amplifier circuit consisting of four standard resistors and an operational amplifier.

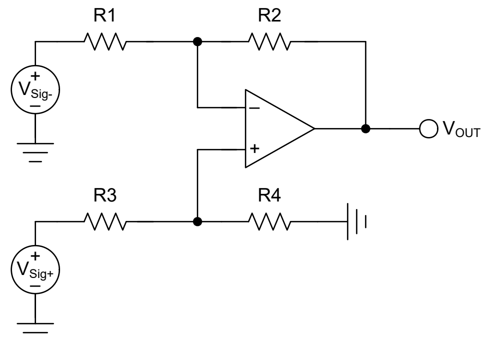

Figure 2-1. Difference Amplifier Circuit

Diff-amp circuits have a differential gain (A_D) which amplifies or attenuates the differential signal voltage, and a common-mode gain (A_{CM}) which amplifies or attenuates the common-mode voltage. Common-mode rejection ratio (CMRR) is defined as the ratio of differential gain to common-mode gain of the amplifier stage.

$$CMRR = \frac{A_D}{A_{CM}} \tag{3}$$

Where,

- A_D is the differential gain of the amplifier stage in V/V
- A_{CM} is the common-mode gain of the amplifier stage in V/V

Often, CMRR is expressed in decibels (dB) as defined by Equation 4.

$$CMRR_{dB} = 20 \cdot Log_{10}\left(\frac{A_D}{A_{CM}}\right) \tag{4}$$

Diff-amps are designed to have high CMRR to reject noise and other errors from the signal chain. The effective CMRR of the gain stage is determined by non-idealities of the discrete components that make up the difference amplifier circuit. The operational amplifier and the resistor network both have CMRR metrics which contribute to the overall CMRR of the diff-amp stage, as detailed in the following.

Operational amplifiers have a CMRR specification that can be found in the amplifier data sheet. For example, OPA387 is an ultra-high precision, zero-drift amplifier with very high CMRR. The electrical characteristics table of the data sheet specifies a CMRR of 150 dB typical when operating on a 5.5-V supply.

Table 2-1. OPA387 Electrical Characteristics: Common-Mode Rejection Ratio

Parameter		Test Conditions		MIN	TYP	MAX	UNIT
CMRR	Common-mode rejection ratio	$(V–) – 0.1\ V < V_{CM} < (V+)$, $V_S = 1.7\ V$		115	138		dB
		$(V–) – 0.2\ V < V_{CM} < (V+) + 0.1\ V$, $V_S = 5.5\ V$	OPA387, OPA2387	140	150		
			OPA4387	130			
		$(V–) – 0.1\ V < V_{CM} < (V+)$, $T_A = –40°C$ to $+125°C$		110	132		
		$(V–) – 0.2\ V < V_{CM} < (V+) + 0.1$, $V_S = 5.5\ V$, $T_A = –40°C$ to $+125°C$		130			

From the typical characteristics section of the OPA387 data sheet, Figure 2-2 shows that the maximum CMRR of the op-amp occurs at DC and low frequencies. As the amplifier's open-loop gain (AOL) decreases over frequency, the CMRR decreases along at a rate of 20 dB per decade. This reduction in CMRR over frequency occurs because the amplifier relies on the high open-loop gain to reject the common-mode error.

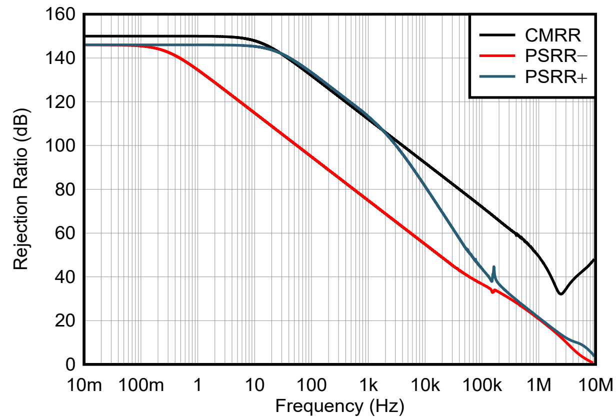

Figure 2-2. PSRR and CMRR vs Frequency, OPA387

The resistive components of the diff-amp shown in Figure 2-1 R_1, R_2, R_3, R_4, also contribute to the total CMRR of the diff-amp stage. Practical resistors have a tolerance specification, often described as a percentage, which indicates the maximum deviation between the absolute resistance and the nominal resistance. For example, a discrete resistor with a nominal resistance of 1 kΩ and a tolerance of ±0.5% can have an absolute resistance between 995 Ω and 1005 Ω. This relationship is described by Equation 5.

$$R_{absolute} = R_{nominal}(1 + t) \tag{5}$$

Where *t* is the absolute tolerance of the resistor in Ω/Ω.

The industry standard is to specify resistor tolerance as a percentage which must be converted into Ω/Ω to be used in the analysis. The percent tolerance $t_{\%}$, is converted to the absolute tolerance *t*, by a division of 100 as in Equation 6. The analysis in this document considers all tolerance metrics in Ω/Ω, even when specified as a percentage.

$$t = \frac{t_{\%}}{100} \tag{6}$$

Where,

- *t* is the absolute tolerance in Ω/Ω
- $t_{\%}$ is the absolute tolerance in %

When the OPA387 is configured as a diff-amp using these 0.5% resistors as shown in Figure 2-3, the resulting CMRR of the diff-amp stage ($CMRR_D$) is much lower than the 150 dB op-amp specification ($CMRR_A$), with a worst-case $CMRR_D$ of only 40 dB.

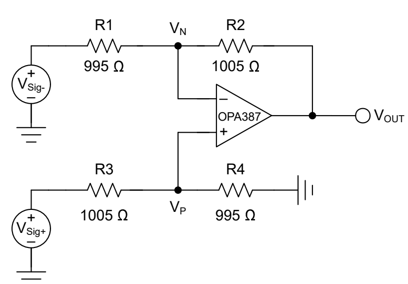

Figure 2-3. Difference Amplifier with 0.5% Tolerance, 1-kΩ Resistors

The degradation of $CMRR_D$ is caused by the deviation in the absolute resistor values due to the resistor tolerance, which produces mismatches between resistor ratios R_2/R_1 and R_4/R_3. The ratiometric mismatch reduces the effective CMRR of the discrete resistor network ($CMRR_R$) which dominates the common-mode performance of the diff-amp stage. This occurs because the difference between the two resistor ratios causes a portion of the common-mode voltage to present as a differential voltage at the op-amp's input terminals which is amplified by the differential gain of the circuit.

The worst-case $CMRR_R$ of a diff-amp using four discrete resistors with tolerance *t*, is given by Equation 7. The detailed derivations for Equation 7 can be found in Section 5.

$$CMRR_R = \frac{G+1}{4t} \tag{7}$$

Where,

- G is the nominal differential gain in V/V
- *t* is the absolute tolerance of the resistors in Ω/Ω

The total CMRR of the diff-amp stage is the parallel combination of the amplifier CMRR and the resistor CMRR, as defined in Equation 8.

$$\frac{1}{CMRR_D} = \frac{1}{CMRR_A} + \frac{1}{CMRR_R} \tag{8}$$

Where,

- $CMRR_D$ is the common-mode rejection ratio of the diff-amp stage in V/V
- $CMRR_A$ is the common-mode rejection ratio of the amplifier in V/V
- $CMRR_R$ is the common-mode rejection ratio of the resistor network in V/V

As shown in Figure 2-4, the $CMRR_D$ performance is dominated by $CMRR_R$. As the AOL of the amplifier decreases over frequency, $CMRR_A$ begins to contribute to the overall CMRR. At high frequencies the common-mode performance is dominated by $CMRR_A$.

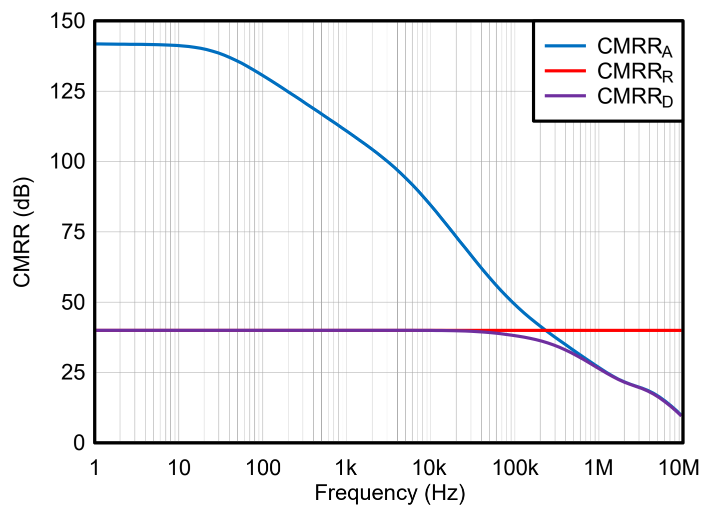

Figure 2-4. Resistor and Op-Amp Contributions to Effective CMRR of Difference Amplifier OPA387 with 0.5% Tolerance Resistors

3 Improving CMRR with Precision Matched Resistor Divider Pairs, RES11A-Q1

The RES11A-Q1 is a precision matched thin-film resistor divider pair optimized for high common-mode rejection and gain accuracy. This device consists of two precision matched resistor dividers, R_{G1}/R_{IN1} and R_{G2}/R_{IN2}, in a small SOT-23 package. The CMRR of a difference amplifier stage is dominated by the ratiometric mismatch between the two resistor dividers. The RES11A-Q1 data sheet specifies the matched ratio tolerance, t_m, of the resistor dividers, which can be used to directly determine the minimum and typical CMRR by Equation 9. The detailed derivations for Equation 9 are found in Section 6.

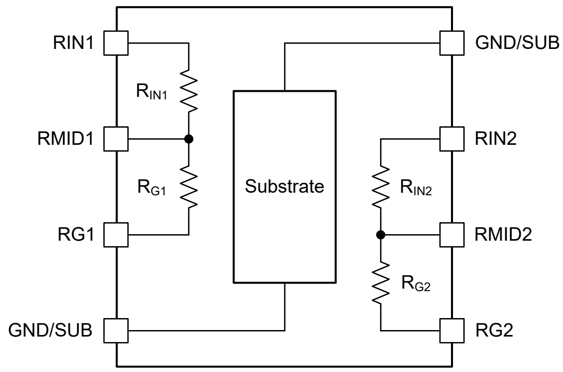

Figure 3-1. RES11A-Q1 Precision Matched Resistor Divider Pair

$$CMRR_R = \frac{G+1}{t_m} \quad (9)$$

Where,

- G is the nominal differential gain in V/V
- t_m is the matched ratio tolerance between resistor dividers R_{G1}/R_{IN1} and R_{G2}/R_{IN2} in Ω/Ω

Figure 3-2 shows the minimum CMRR of a difference amplifier using the RES11A-Q1 precision matched pair compared to standard discrete resistors.

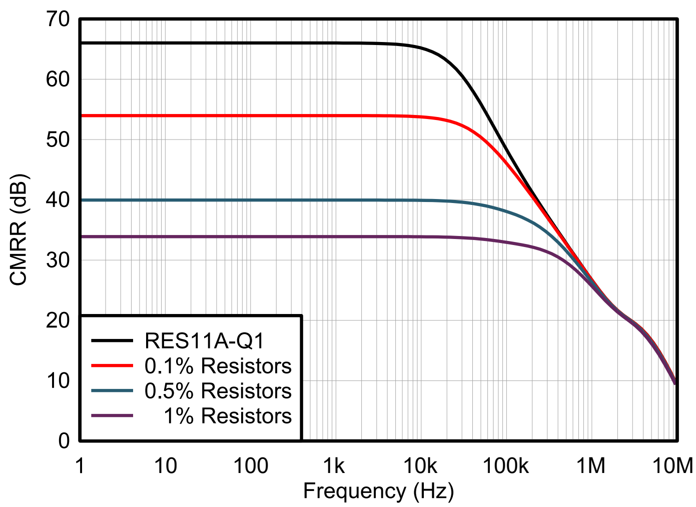

Figure 3-2. Minimum CMRR of Difference Amplifier with RES11A-Q1 vs Discrete Resistors OPA387, Gain = 1 V/V

The effective CMRR can be further improved by increasing the differential gain of the diff-amp stage. The RES11A-Q1 is available in various ratios between 1 and 10, which allows for a variety of fixed-gain configurations. Figure 3-3 shows the minimum CMRR of a difference amplifier configured with common RES11A-Q1 gain ratios.

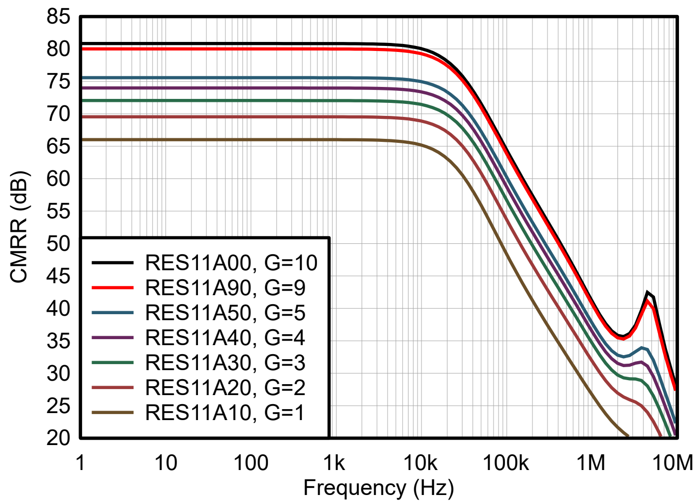

Figure 3-3. Minimum CMRR of Difference Amplifier with Various RES11A-Q1 Gain Options, OPA387

Table 3-1 shows the various gain ratios of the RES11A-Q1. These ratios can be configured inversely to achieve attenuation by simply rotating the device package 180°. The nominal gain ratio, or attenuation ratio, is used in Equation 9 to determine the minimum and typical CMRR of the RES111A-Q1 when configured in a difference amplifier circuit.

Table 3-1. RES11A-Q1 Gain Ratios

PART NUMBER	NOMINAL RATIO
RES11A10-Q1	1:1
RES11A15-Q1	1:1.5
RES11A16-Q1	1:1.667
RES11A20-Q1	1:2
RES11A25-Q1	1:2.5
RES11A30-Q1	1:3
RES11A40-Q1	1:4
RES11A50-Q1	1:5
RES11A90-Q1	1:9
RES11A00-Q1	1:10

4 Derive Differential and Common-Mode Gain, Difference Amplifier

This section details the step-by-step derivations for differential and common-mode gain of a difference amplifier circuit. These gain equations are used to determine the CMRR of a difference amplifier as a function of the absolute resistance of the resistor network. The resulting relationships are used in the following sections to derive the simplified CMRR equations for both discrete resistor tolerance *t*, and matched ratio tolerance t_m.

Figure 4-1 illustrates a typical difference amplifier circuit. Assuming an ideal op-amp, Kirchoff's Current Law (KCL) and Kirchoff's Voltage Law (KVL) can be applied to determine the transfer function. The ideal op-amp assumptions are that the voltage at the inverting input (V_N) is equal to the voltage at the non-inverting input (V_P), and there is zero current flowing through the input terminals.

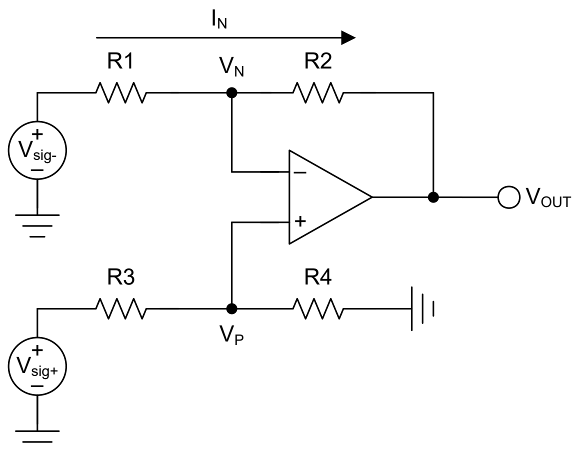

Figure 4-1. Difference Amplifier Circuit with Ideal Op-Amp

Analysis of Figure 4-1 using KVL, KCL, and ideal op-amp assumptions produces the following equations.

$$V_N = V_P \tag{10}$$

$$V_P = \left(\frac{R_4}{R_3 + R_4}\right)V_{Sig+} \tag{11}$$

$$V_{OUT} = V_N - I_N R_2 \tag{12}$$

$$I_N = \frac{V_{Sig-} - V_N}{R_1} \tag{13}$$

Combining the previous equations results in Equation 14.

$$V_{OUT} = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)V_{Sig+} - \left(\frac{R_2}{R_1}\right)V_{Sig-} \tag{14}$$

Some trivial algebra rewrites Equation 14 in a more intuitive form, Equation 15. Note that in this form, Equation 15 is represented as a combination of resistor dividers.

$$V_{OUT} = \frac{\left(\frac{R_4}{R_3 + R_4}\right)V_{Sig+} - \left(\frac{R_2}{R_1 + R_2}\right)V_{Sig-}}{\left(\frac{R_1}{R_1 + R_2}\right)} \tag{15}$$

At this point in the analysis, it is useful to consider the differential and common-mode voltage components of the input signal. In Figure 4-2, the difference amplifier circuit is redrawn to show the input voltage as a combination of differential and common-mode voltage sources. This shows that V_{Sig+} and V_{Sig-} each consist of half of the input differential voltage, of opposite polarity, referenced to the input common-mode voltage, as expressed by Equation 16 and Equation 17.

$$V_{Sig+} = V_{CM} + \frac{V_{Diff}}{2} \tag{16}$$

$$V_{Sig-} = V_{CM} - \frac{V_{Diff}}{2} \tag{17}$$

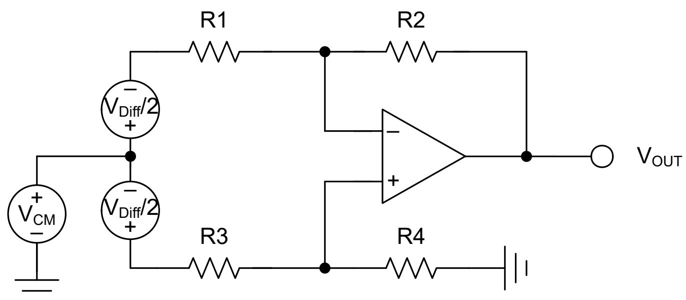

Figure 4-2. Difference Amplifier With Differential and Common-Mode Input Signals

Rewriting Equation 15 considering the differential and common-mode components of the input signal produces Equation 18.

$$V_{OUT} = \frac{\left(\frac{R_4}{R_3 + R_4}\right)\left(V_{CM} + \frac{V_{Diff}}{2}\right) - \left(\frac{R_2}{R_1 + R_2}\right)\left(V_{CM} - \frac{V_{Diff}}{2}\right)}{\left(\frac{R_1}{R_1 + R_2}\right)} \tag{18}$$

Superposition allows the differential and common-mode voltage components to be considered independently, as shown in Figure 4-3 and Figure 4-4. Applying superposition to Equation 18 produces the differential-mode transfer function as defined by Equation 19 and the common-mode transfer function as defined by Equation 20.

$$A_D = \frac{V_{OUT}}{V_{Diff}} = \frac{1}{2}\frac{\left(\frac{R_4}{R_3+R_4}\right)+\left(\frac{R_2}{R_1+R_2}\right)}{\left(\frac{R_1}{R_1+R_2}\right)} \quad (19)$$

$$A_{CM} = \frac{V_{OUT}}{V_{CM}} = \frac{\left(\frac{R_4}{R_3+R_4}\right)-\left(\frac{R_2}{R_1+R_2}\right)}{\left(\frac{R_1}{R_1+R_2}\right)} \quad (20)$$

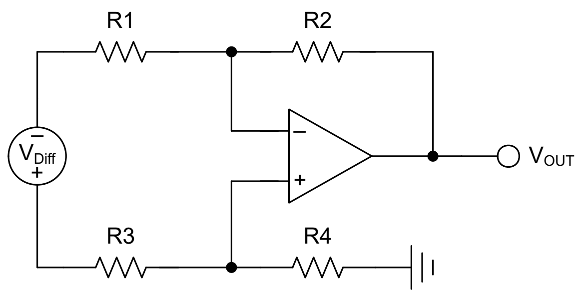

Figure 4-3. Superposition: Differential-Mode

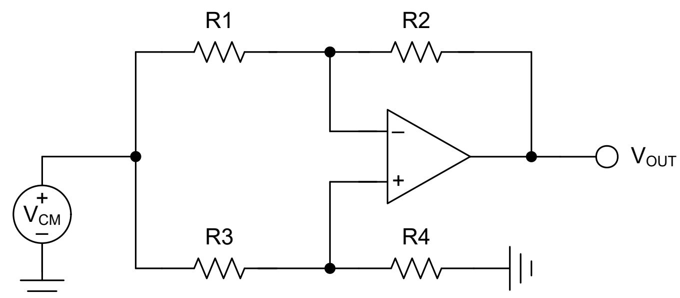

Figure 4-4. Superposition: Common-Mode

Combining the differential and common-mode gain equations with the definition of CMRR from Equation 3, results in Equation 21.

$$CMRR = \frac{1}{2}\frac{\left(\frac{R_4}{R_3+R_4}\right)+\left(\frac{R_2}{R_1+R_2}\right)}{\left(\frac{R_4}{R_3+R_4}\right)-\left(\frac{R_2}{R_1+R_2}\right)} \quad (21)$$

In this form, it is clear that the CMRR of the resistor network is determined by the difference between the two resistor dividers R_2/R_1 and R_4/R_3. The CMRR equation can also be expressed in the form below, which is used for the analysis in Section 5 and Section 6.

$$CMRR = \frac{1}{2}\frac{2R_2R_4 + R_1R_4 + R_2R_3}{R_1R_4 - R_2R_3} \quad (22)$$

5 Derive CMRR for Discrete Resistor Tolerance

A common assumption in difference amplifier circuits is that the ratio of R_4 and R_3 is equal to the ratio of R_2 and R_1, as described by Equation 23.

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} = \frac{R_g}{R_{in}} \tag{23}$$

This assumption is useful because it allows the differential gain equation to be reduced to the form in Equation 24. This is the simplified gain equation for a difference amplifier circuit.

$$A_D = \frac{R_g}{R_{in}} \tag{24}$$

Combining Equation 23 with Equation 20 shows that if the resistor ratios are perfectly matched, the common-mode gain (A_{CM}) is 0 V/V, and therefore the common-mode rejection ratio of the resistor network ($CMRR_R$) is infinite.

$$A_{CM} = \frac{\left(\frac{R_g}{R_{in}+R_g}\right) - \left(\frac{R_g}{R_{in}+R_g}\right)}{\left(\frac{R_{in}}{R_{in}+R_g}\right)} = 0\ V/V \tag{25}$$

In practice, the variation in absolute resistance due to resistor tolerance produces mismatches between the absolute ratios of R_4/R_3 and R_2/R_1. The ratio mismatch presents an asymmetrical resistor divider effect at the amplifier's input terminals. Any common-mode input voltage is attenuated unequally between the two resistor dividers and presents as a small differential voltage which is amplified by the differential gain of the circuit, thus degrading the CMRR performance of the differential stage.

Considering a differential amplifier circuit consisting of four discrete resistors with tolerance *t*, the worst-case ratio matching occurs when the absolute resistor values differ from the nominal resistor values as shown in Figure 5-1 in which,

$$R_1 = R_{1N}(1+t) \tag{26}$$

$$R_2 = R_{2N}(1-t) \tag{27}$$

$$R_3 = R_{3N}(1-t) \tag{28}$$

$$R_4 = R_{4N}(1+t) \tag{29}$$

Where,

- R_{XN} is the nominal resistance of resistor R_X in Ω
- *t* is the absolute tolerance of the resistor in Ω/Ω

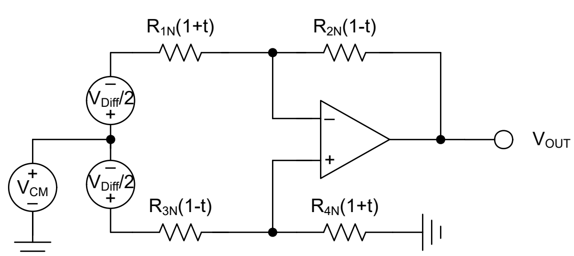

Figure 5-1. Worst-Case Resistor Matching of Difference Amplifier Circuit

The nominal resistor ratios determine the nominal gain of the difference amplifier stage.

$$\frac{R_{4N}}{R_{3N}} = \frac{R_{2N}}{R_{1N}} = G \tag{30}$$

Where,

- R_{XN} is the nominal resistance of resistor R_X in Ω
- G is the nominal differential gain of the amplifier stage in V/V

The contribution of resistor tolerance to the overall common-mode rejection ratio of the difference amplifier can be determined in the worst-case by combining Equation 26 through Equation 29 with Equation 22.

$$CMRR_R = \frac{1}{2}\frac{2R_{2N}R_{4N}\left(1-t\right)\left(1+t\right) + R_{1N}R_{4N}(1+t)^2 + R_{2N}R_{3N}(1-t)^2}{R_{1N}R_{4N}(1+t)^2 - R_{2N}R_{3N}(1-t)^2} \tag{31}$$

Applying the relationship defined in Equation 30,

$$CMRR_R = \frac{1}{2}\frac{2G^2R_{1N}R_{3N}\left(1-t^2\right) + GR_{1N}R_{3N}(1+t)^2 + GR_{1N}R_{3N}(1-t)^2}{GR_{1N}R_{3N}(1+t)^2 - GR_{1N}R_{3N}(1-t)^2} \tag{32}$$

Which reduces to

$$CMRR_R = \frac{G+1+t^2\left(1-G\right)}{4t} \tag{33}$$

Standard resistor tolerances are very small, typically 1% or less, therefore it is common to further simplify the equation for $t \ll 1$. The contribution of discrete resistor tolerance to the overall CMRR of the difference amplifier for $t \ll 1$ is defined by Equation 34.

$$CMRR_R \approx \frac{G+1}{4t} \tag{34}$$

Where,

- G is the nominal differential gain in V/V
- t is the absolute tolerance of the resistors in Ω/Ω

6 Derive CMRR for Matched Ratio Tolerance

As derived in Section 4, the CMRR of a difference amplifier stage is dominated by the mismatch between the two resistor divider ratios. The absolute accuracy of the four resistor values does not directly contribute to the CMRR performance. The RES11A-Q1 consists of two precision thin-film resistor dividers: R_{G1}/R_{IN1} and R_{G2}/R_{IN2}. The ratio tolerance t_D of each resistor divider is specified in the RES11A-Q1 data sheet and is defined by the following relationships.

$$\frac{R_{G1}}{R_{IN1}} = G\left(1 + t_{D1}\right) \tag{35}$$

$$\frac{R_{G2}}{R_{IN2}} = G\left(1 + t_{D2}\right) \tag{36}$$

Where,

- G is the nominal gain ratio in V/V
- t_{D1} is the ratio tolerance of divider 1 in Ω/Ω
- t_{D2} is the ratio tolerance of divider 2 in Ω/Ω

From the previous equations, it is also shown that:

$$R_{G1} = G(1 + t_{D1})R_{IN1} \tag{37}$$

$$R_{G2} = G(1 + t_{D2})R_{IN2} \tag{38}$$

Figure 6-1 shows the RES11A-Q1 in a difference amplifier configuration. From the analysis in Section 4, the common-mode rejection ratio of the resistor network is defined by Equation 39.

$$CMRR_R = \frac{1}{2}\frac{2R_{G1}R_{G2} + R_{IN1}R_{G2} + R_{G1}R_{IN2}}{R_{IN1}R_{G2} - R_{G1}R_{IN2}} \tag{39}$$

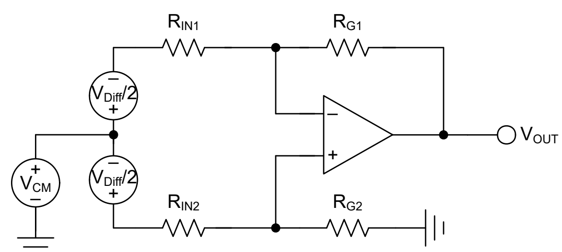

Figure 6-1. RES11A-Q1 Difference Amplifier Circuit

The effect of the ratio tolerance is considered by substituting the relationships from Equation 37 and Equation 38 into Equation 39.

$$CMRR_R = \frac{1}{2}\frac{2G^2R_{IN1}R_{IN2}\left(1 + t_{D1}\right)\left(1 + t_{D2}\right) + GR_{IN1}R_{IN2}\left(1 + t_{D2}\right) + GR_{IN1}R_{IN2}\left(1 + t_{D1}\right)}{GR_{IN1}R_{IN2}(1 + t_{D2}) - GR_{IN1}R_{IN2}(1 + t_{D1})} \tag{40}$$

Which reduces to Equation 41.

$$CMRR_R = \frac{G + 1 + G(t_{D1} + t_{D2} + t_{D1}t_{D2}) + t_{D1} + t_{D2}}{t_{D2} - t_{D1}} \tag{41}$$

The RES11A-Q1 tolerances t_{D1} and t_{D2} are very small, with a maximum tolerance of ±0.05%. Therefore, it is consistent with Equation 34 for standard resistors to further simplify the equation for t_D << 1, resulting in Equation 42.

$$\text{CMRR}_R \approx \frac{G+1}{t_{D2} - t_{D1}} \tag{42}$$

The RES11A-Q1 data sheet specifies the matched ratio tolerance t_m, as the difference between the absolute ratio tolerances of the two resistor dividers, as defined in Equation 43. The matched ratio tolerance specification describes the maximum and typical mismatch between the two resistor divider ratios.

$$t_m = t_{D2} - t_{D1} \tag{43}$$

Therefore, the simplified equation for the common-mode rejection ratio of the RES11A-Q1 is expressed by Equation 44. This equation can be used with data sheet specifications to directly calculate the minimum and typical CMRR_R of the RES11A-Q1 precision matched resistor divider pair.

$$CMRR_R = \frac{G+1}{t_m} \tag{44}$$

Where,

- G is the nominal differential gain in V/V
- t_m is the matched ratio tolerance between resistor dividers R_{G1}/R_{IN1} and R_{G2}/R_{IN2} in Ω/Ω

7 Summary

The common-mode rejection ratio (CMRR) of a difference amplifier is dominated by the matched ratio tolerance of the resistor network. The matched ratio tolerance of four discrete resistors can be up to four times the magnitude of each resistor's absolute tolerance. The RES11A-Q1 data sheet specifies matched ratio tolerance, t_m, which can be used to directly calculate the minimum and typical CMRR when configured in a differential amplifier circuit. Equations were derived to determine the CMRR of a difference amplifier as a function of absolute resistance, discrete resistor tolerance, and matched ratio tolerance. The RES11A-Q1 features precision ratiometric matching to improve the effective CMRR of differential amplifier circuits.

8 References

1. Texas Instruments, *RES11A-Q1 Automotive, Matched, Thin-Film Resistor Dividers With 1-kΩ Inputs*, data sheet.
2. Texas Instruments, *OPAx387 Ultra-High Precision, Zero-Drift, Low-Input-Bias-Current Op Amps*, data sheet.
3. *IEEE, Common Mode Rejection Ratio in Differential Amplifiers*.
4. *IEEE, Differential Signals, Rules to Live By*.
5. All About Circuits, *The Why and How of Differential Signaling*, technical article.