Instrumentation Amplifiers

Deriving the V_{CM} versus V_{OUT} Plot for the ISL2853x Instrumentation Amplifier

Abstract

The common-mode voltage-versus-output voltage plot (also known as the diamond plot) of the ISL2853x Instrumentation Amplifier (INA) in Figure 1, consists of six sections that represent the common-mode limits introduced by each amplifier (Figure 2). These limits are shown aspositive and negative output voltages. This application note explains how to derive the diamond plot.
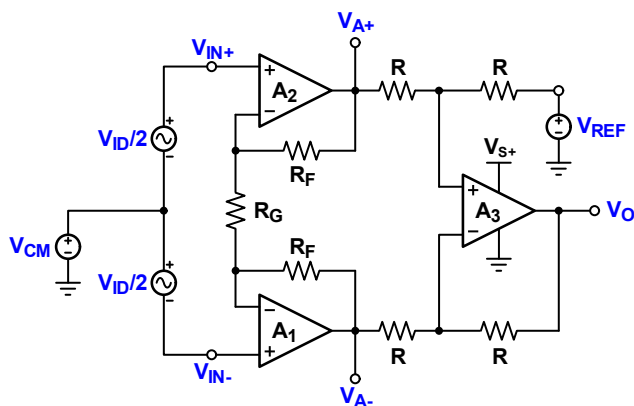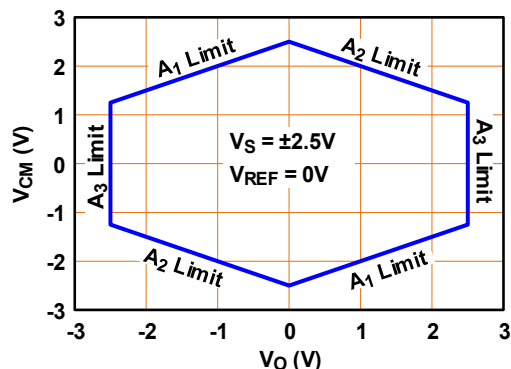

Figure 1. ISL2853x Schematic

Figure 2. V_{CM} versus V_O Plot

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Related Literature

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• ISL28533, ISL28534, ISL28535 device pages

1. INA Fundamentals

The input voltages of the instrumentation amplifier (V_{IN+} and V_{IN-}) are the sum of the common-mode voltage (V_{CM}) and half the differential input signal ($V_{ID}/2$):

$$(EQ. 1) \quad V_{IN+} = V_{CM} + \frac{V_{ID}}{2} \quad \text{and} \quad V_{IN-} = V_{CM} - \frac{V_{ID}}{2}$$

The resulting output voltages of the input stage are therefore:

$$(EQ. 2) \quad V_{A+} = V_{CM} + G_D \cdot \frac{V_{ID}}{2} \quad \text{and} \quad V_{A-} = V_{CM} - G_D \cdot \frac{V_{ID}}{2}$$

Where G_D is the differential signal gain, given with: $G_D = 1 + \frac{2R_F}{R_G}$

Per Equation 2, the input amplifiers (A_1 and A_2) only amplify the differential signal component, while the common-mode voltage is passed through at a gain of one.

The subsequent difference amplifier (diff-amp) subtracts V_{A-} from V_{A+}; therefore, removing the input common-mode voltage and only amplifying the difference of the differential input signal. It also adds an output common-mode potential in the form of the reference voltage (V_{REF}) to produce the output voltage:

$$(EQ. 3) \quad V_O = V_{A+} - V_{A-} + V_{REF} \quad = \quad G_D \cdot \left[\frac{V_{ID}}{2} - \left(-\frac{V_{ID}}{2} \right) \right] + V_{REF} = V_{OD} + V_{REF}$$

It is important to notice that the differential input voltage at each input of the diff-amp can only be half the differential output voltage to avoid output saturation. Therefore:

$$(EQ. 4) \quad G_D \cdot \frac{V_{ID}}{2} = \frac{V_{OD}}{2}$$

2. Common-Mode Limits

The supply rails limits the input and output voltage ranges of each amplifier; therefore, also limiting the input common-mode range of the entire instrumentation amplifier. Denoting the upper common-mode limit with V_{CMH} and lower common-mode limits with V_{CML}, we establish the equations for the upper and lower voltage limits at V_{A+} and V_{A-} with the help of Figure 3.

Figure 3. Input and Output Voltage Relations of the Diff-Amp

Figure 3 shows the blue shaded areas as the diff-amp input voltages that cause output voltages higher than the reference voltage, and the orange shaded areas as the input voltages that cause output voltages lower than the reference voltage.

The maximum positive and negative output voltage differences, V_{ODp} and V_{ODn}, are defined as:

(EQ. 5) $$V_{ODp} = V_{OH} - V_{REF}$$

(EQ. 6) $$V_{ODn} = V_{REF} - V_{OL}$$

In the following calculations, it is important to distinguish between these output voltage definitions, and to assign the V_{ODp} definition to positive input voltages, $V_{A+} > V_{A-}$, and the V_{ODn} definition to negative input voltages, $V_{A+} < V_{A-}$.

2.1   Deriving V_{CMH} at $V_{A+(max)}$ (for Positive Diff-Amp Input Voltages)

The maximum voltage at VA+ is the sum of the maximum input common-mode voltage, V_{CMH}, and the maximum possible differential component, $G_D \cdot V_{ID}/2$:

(EQ. 7) $$V_{A+(max)} = V_{CMH} + G_D \cdot \frac{V_{ID}}{2}$$

From Equation 4 we know that the amplified differential input component must not be larger than half the differential output component to avoid output saturation. We can therefore rewrite Equation 7 as:

(EQ. 8) $$V_{A+(max)} = V_{CMH} + \frac{V_{OD}}{2}$$

Due to the positive polarity of the differential output component, we substitute V_{OD} with V_{ODp} in Equation 5:

(EQ. 9) $$V_{A+(max)} = V_{CMH} + \frac{V_{OH} - V_{REF}}{2}$$

Because $V_{A+(max)}$ is limited to V_{OH}, we substitute $V_{A+(max)}$ with V_{OH}:

(EQ. 10) $$V_{OH} = V_{CMH} + \frac{V_{OH} - V_{REF}}{2}$$

and then solve for V_{CMH}:

(EQ. 11) $$V_{CMH} = \frac{V_{OH} + V_{REF}}{2}$$

To calculate the output voltage of the diff-amp when its V_{A+} input is at $V_{A+(max)}$, we determine the voltage at the complementary input, V_{A-}, with:

(EQ. 12) $$V_{A-} = V_{CMH} - \frac{V_{OD}}{2} = V_{CMH} - \frac{V_{OH} - V_{REF}}{2}$$

Calculating the output voltage using Equations 3, 9, and 12 confirms that:

(EQ. 13) $$V_O = V_{A+} - V_{A-} + V_{REF} = V_{OH}$$

Therefore, Equations 11 and 13 provide the first point in the diamond diagram.

2.2   Deriving V_{CML} at $V_{A+(min)}$ (for Negative Diff-Amp Input Voltages)

The minimum voltage at V_{A+} can be expressed through:

(EQ. 14) $$V_{A+(min)} = V_{CML} - G_D \cdot \frac{V_{ID}}{2}$$

Again, the amplified differential input component must not be larger than half the differential output component, so we can write Equation 14 as:

(EQ. 15) $$V_{A+(min)} = V_{CML} - \frac{V_{OD}}{2}$$

Due to the negative polarity of the differential output component, we substitute V_{OD} with V_{ODn} in Equation 6:

(EQ. 16) $$V_{A+(min)} = V_{CML} - \frac{V_{REF} - V_{OL}}{2}$$

Because $V_{A+(min)}$ is limited to V_{OL}, we substitute $V_{A+(min)}$ with V_{OL}:

(EQ. 17) $$V_{OL} = V_{CML} - \frac{V_{REF} - V_{OL}}{2}$$

and then solve for V_{CML}:

(EQ. 18) $$V_{CML} = \frac{V_{OL} + V_{REF}}{2}$$

To calculate the output voltage of the diff-amp when its V_{A+} input is at $V_{A+(min)}$, we determine the voltage at the complementary input, V_{A-}, with:

(EQ. 19) $$V_{A-} = V_{CML} + \frac{V_{OD}}{2} = V_{CML} + \frac{V_{REF} - V_{OL}}{2}$$

Calculating the output voltage using Equations 3, 16, and 19 confirms that:

(EQ. 20) $$V_O = V_{A+} - V_{A-} + V_{REF} = V_{OL}$$

Now, Equations 18 and 20 provide the second point in the diamond diagram.

2.3   Deriving V_{CMH} and V_{CML} at $V_{A-(max)}$ and $V_{A-(min)}$

The input common-mode limits for V_{A-} can be derived the same way as done for V_{A+}. But rest assured, due to the symmetrical structure of the INA, they must yield the same voltage levels, albeit slightly different voltage equations. The corresponding output voltages; however, are complementary to the previous ones, due to the opposite polarity of V_{A-} and V_{A+}. Avoiding the precious long-winded derivations, the wanted common-mode and output levels are given below:

For $V_{A-(max)}$ the maximum common-mode voltage is:

(EQ. 21) $$V_{CMH} = V_{OH} - \frac{V_{REF} - V_{OL}}{2}$$

And the corresponding output voltage is:

(EQ. 22) $$V_O = V_{OL}$$

For $V_{A-(min)}$ the maximum common-mode voltage is:

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(EQ. 23) $V_{CML} = V_{OL} + \dfrac{V_{OH} - V_{REF}}{2}$

And the corresponding output voltage is:

(EQ. 24) $V_O = V_{OH}$

Equations 21 to 24 provide Points 3 and 4 in the diamond diagram.

2.4   Deriving V_{CMH} and V_{CML} for Zero Differential Input

Without a differential input signal component, the input common-mode range solely depends on the design specification of the input stage, as the output voltage remains at supply mid-point, or V_{REF}. for the ISL2853x family of instrumentation amplifiers, the V_{CM} range is specified with:

(EQ. 25) $V_{CM(max)} = V_{S+} - 0.1V$

(EQ. 26) $V_O\big|_{V_D=0} = V_{REF}$

(EQ. 27) $V_{CM(min)} = V_{S-} + 0.1V$

(EQ. 28) $V_O\big|_{V_D=0} = V_{REF}$

Equations 25 to 28 provide Points 5 and 6 in the diamond diagram.

2.5   Creating the Diamond Plot

For convenience, Table 1 lists the relevant equations for calculating the critical points in the diamond diagram.

Table 1.   Important Equations for Developing the V_{CM} vs V_O Plot

Point	Equations	Common-Mode Voltage	Output Voltage
1	11, 13	$V_{CMH} = (V_{OH} + V_{REF})/2$	$V_O = V_{OH}$
2	18, 20	$V_{CML} = (V_{OL} + V_{REF})/2$	$V_O = V_{OL}$
3	21, 22	$V_{CMH} = V_{OH} + (V_{OL} - V_{REF})/2$	$V_O = V_{OL}$
4	23, 24	$V_{CML} = V_{OL} + (V_{OH} - V_{REF})/2$	$V_O = V_{OH}$
5	25, 26	$V_{CM(max)} = V_{S+} - 0.1V$	$V_O = V_{REF}$
6	26, 27	$V_{CM(min)} = V_{S+} + 0.1V$	$V_O = V_{REF}$

Figures 4 and 5 show the diamond plots for single and dual supply operation. Due to the rail-to-rail output drive capability of the device, V_{OH} and V_{OL} are assumed with V_{S+} and V_{S-}, respectively. The voltages of the critical points in the diagram have been calculated using the equations in Table 1.

Point	V_{CM} (V)	V_O (V)
1	3.75	5
2	1.25	0
3	3.75	0
4	1.25	5
5	4.9	2.5
6	0.1	2.5
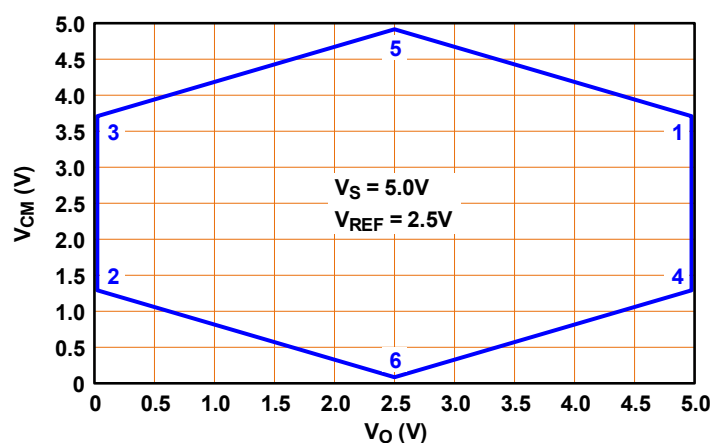
Figure 4. ISL2853x Diamond Plots for Single Supply Operation

Point	V_{CM} (V)	V_O (V)
1	1.25	2.5
2	-1.25	-2.5
3	1.25	-2.5
4	-1.25	2.5
5	2.4	0
6	-2.4	0
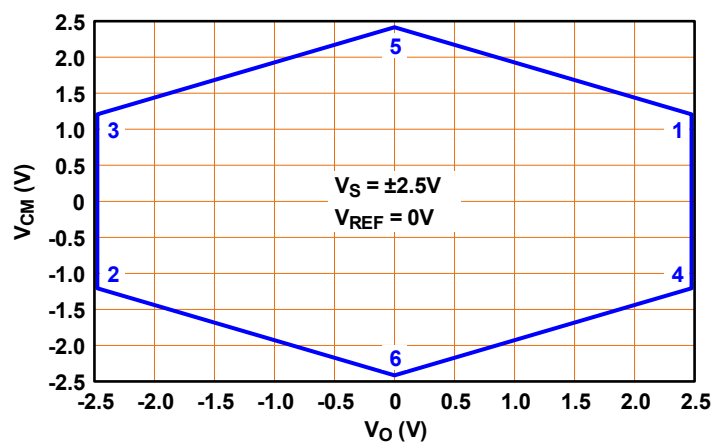
Figure 5. ISL2853x Diamond Plots for Dual Supply Operation

3.   Interpreting the Diamond Plot

Figure 6 identifies which amplifier is limiting the common-mode voltage within what range.
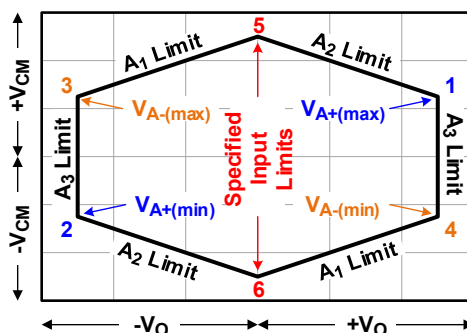

Figure 6. Diamond Plot Identifying the Limiting Amplifiers

As previously mentioned, the specified input limits represent the minimum and maximum common-mode voltages without a differential input signal present.

Starting at Point 5, an increasing positive differential input signal ($+V_D/2$ at INA+, $-V_D/2$ at INA-), requires a decrease in common-mode voltage to prevent amplifier A_2 from exceeding V_{OH}, the output saturation level. At the same time, the output of A_1, V_{A-}, becomes more negative by the same amount A_2 has turned positive, but due to the high V_{CM}, A_1 is far from its lower saturation level, V_{OL} (see Figure 3 for comparison). Therefore, A_2 is the only amplifier limiting V_{CM} between Point 5 and Point 1.

At Point 1, A_2 and A_1 apply their maximum differential output voltages to the inputs of the diff-amp. This causes the output of A_3 to reach its output saturation voltage, V_{OH}. At this point, changing the input common-mode level high to low (single supply operation), or from positive to negative (dual supply operation), leads to the horizontal line from Point 1 to Point 4. Along this line, changing V_{CM} does not affect the output of A_3, and A_3 remains the only limiting amplifier until Point.

At Point 4, A_2 and A_1 are still providing their maximum output voltages. The change in V_{CM}, however, draws the positive output of A_2 away from V_{OH}, but causes the negative output of A_1 to reach its lower saturation level, V_{OL}. Reducing the differential input signal allows the decrease in V_{CM} towards more negative or lower levels, but only to the amount of the output saturation level of A_1, V_{OL}. Therefore, A_1 is the V_{CM} limiting amplifier between Point 4 and Point 6.

Note: The previous discussion concerned positive input signals. The same V_{CM} versus V_O dependency exists for negative input signals. In this case, the right side of the diamond plot is mirrored to the left side.

4.   Revision History

Rev.	Date	Description
1.00	May.22.20	Initial release

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