Are you violating your op amp's input-common-mode range?

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You go through a process to select an operational amplifier for your circuit by considering the most critical parameters of your application. Some of the parameters you review may include supply voltage, gain-bandwidth product, slew rate, and input noise voltage. You also must account for input common-mode range, a key parameter important for all op-amp circuits.

Engineers who have worked with op amps throughout their careers likely have experienced situations in which an op amp was behaving in an unexpected manner. The nice thing about op amps is that their outputs often tell the story. In many cases, if something is not right, it shows up in an obvious way at the output pin. Limitations at the output stage can cause undesirable output waveforms. Perhaps too much capacitance on the output is causing an oscillation, or clipping occurs before reaching the full rail voltage because the output stage’s voltage swings are less than the supply-rail voltage.

Strange behavior can also appear at the op amp’s output that has nothing to do with the output stage. The undesirable output signal may result from something wrong at the input side of the device. One of the most common issues with op amps is a violation of the device’s input common-mode range. But what exactly is input common-mode range, and what is the impact of violating or exceeding it?

Input common-mode voltage, \( V_{ICM} \), is one of the first specifications an engineer thinks of when considering op-amp inputs, but it may lead to some initial confusion. \( V_{ICM} \) describes a voltage level and is the average voltage at the inverting and noninverting input pins (Figure 1). It is commonly expressed using the following equation:

\[
V_{ICM} = \frac{V_{IN+} + V_{IN-}}{2}
\]

Another way to think of \( V_{ICM} \) is that it is the voltage level common to both noninverting and inverting inputs, \( V_{IN+} \) and \( V_{IN-} \). In most applications \( V_{IN+} \) is very close to \( V_{IN-} \) because closed-loop negative feedback causes one input pin to closely track the other such that the difference between \( V_{IN+} \) and \( V_{IN-} \) is close to zero. This situation is true for many common circuits, including voltage followers and inverting and noninverting configurations. In these cases, you commonly assume that \( V_{IN+} = V_{IN-} = V_{ICM} \) because these voltages are approximately the same.
Another term to describe op-amp inputs is input common-mode range, $V_{ICMR}$ or, more correctly, input common-mode voltage range. Data sheets most often use this parameter, and it is the one that circuit designers should be most concerned about. $V_{ICMR}$ defines a range of common-mode input voltages that results in proper operation of the op amp and describes how close the inputs can get to either supply rail.

Another way to think of $V_{ICMR}$ is that it describes a range that minimum $V_{ICMR_{MIN}}$ and maximum $V_{ICMR_{MAX}}$ describe, as the following equation shows:

$$V_{ICMR} = V_{ICMR_{MAX}} - V_{ICMR_{MIN}}$$

where $V_{ICMR_{MIN}}$ is the limit relative to the $V_{CC-}$ supply rail and $V_{ICMR_{MAX}}$ is the limit relative to the $V_{CC+}$ supply rail (Figure 2).

When the op amp exceeds $V_{ICMR}$, the device may not perform normal linear operation. Therefore, you must understand the entire range of the input signal and ensure that the op amp does not exceed $V_{ICMR}$.

Another point of confusion may be that $V_{ICM}$ and $V_{ICMR}$ are not standard abbreviations, and various data sheets from various IC suppliers often use different terminology, including $V_{CM}$, $V_{IC}$, and $V_{CMR}$. Consequently, you must understand that the specification you’re looking for is more than a particular input voltage; it is an input voltage range.

$V_{ICMR}$ varies among op amps

An op amp’s design specifications and the process technology it uses dictate the device’s input stage. For example, the input stage of a CMOS op amp differs from that of a bipolar op amp, which differs from that of a JFET op amp. It is important to note that these differences exist among various op amps.

Table 1 shows several examples of Texas Instruments op amps and their $V_{ICMR}$. The maximum-supply-range column describes split- and single-supply limitations. From the table it is clear that the input range, $V_{ICMR}$, differs from op amp to op amp. Depending on the type of device, $V_{ICMR}$ may fall within or beyond the supply rails. Hence, never assume that an op amp can receive a specific input signal range until you verify it in the data-sheet specifications.
One special case worth mentioning for wide input ranges is the rail-to-rail-input op amp. Although the name implies an op amp whose input can span the entire supply-rail range, not all rail-to-rail-input devices cover the entire supply range, as you might assume. Many rail-to-rail-input op amps, such as TI’s OPA333, do span the entire supply range, but others fall short and are misleading in their description. Again, it is critical to review the specified input range in the data sheet.

**Examples of violating $V_{ICMR}$**

Violations of $V_{ICMR}$ commonly occur in single-supply op-amp applications using 3.3V, 5V, or other low-voltage supplies. In these applications, the input signal range typically is narrow, and you must understand the input signal and $V_{ICMR}$ to ensure proper op-amp operation. An op amp that violates $V_{ICMR}$ can have undesirable output behavior, such as clipping the signal at voltage levels lower than you expect, voltage shifts in the output signal, phase reversal, or the output’s prematurely reaching one of the supply-rail voltages.

<table>
<thead>
<tr>
<th>Device</th>
<th>Technology</th>
<th>$V_{ICMIN}$ (V)</th>
<th>$V_{ICMAX}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLE2002A</td>
<td>JFET input</td>
<td>±19/38</td>
<td>$V_{CC}$+3.4</td>
</tr>
<tr>
<td>TLC2272</td>
<td>LinCMOS</td>
<td>±3/16</td>
<td>($V_{CC}$)−0.3</td>
</tr>
<tr>
<td>TL071</td>
<td>BiCMOS</td>
<td>±7.5/15</td>
<td>($V_{CC}$)+1.15</td>
</tr>
<tr>
<td>OPA333</td>
<td>CMOS/rail-to-rail input</td>
<td>±2.75/5.5</td>
<td>($V_{CC}$)+0.1</td>
</tr>
<tr>
<td>OPA735</td>
<td>CMOS</td>
<td>±6/12</td>
<td>($V_{CC}$)+0.1</td>
</tr>
</tbody>
</table>

To better understand the effects of exceeding $V_{ICMR}$, some examples with violations follow.

Two op amps with different $V_{ICMR}$ specifications demonstrate these effects. These devices have rail-to-rail outputs to rule out limitations due to the output stage. A single-supply voltage-follower circuit is used to evaluate both devices (Figure 3). All tests took place on a lab bench at a room temperature of approximately 25°C.

The first example uses a TLC2272 op amp with a $V_{CC}$ of 10V. The data sheet describes its typical $V_{ICMR}$ range as −0.3 to +4.2V for a 5V supply voltage at 25°C. Note that the input limitation is near the positive supply rail, at 0.8V below $V_{CC}$. The resulting input limit near $V_{CC}$ should be approximately 9.2V.
To test the circuit, apply a 300-Hz sine wave with a dc offset of half the $V_{CC}$ voltage, or 5V, to the input. Adjust the ac amplitude until you see a change at $V_{OUT}$. When you apply 10V p-p input, $V_{OUT}$ shows a clipped signal near the positive rail but not near the negative rail. This undesirable behavior near the positive rail is what you would expect if the input exceeds 9.2V. For $V_{IN}$ of 0 to 9.2V, $V_{OUT}$ shows a proper waveform, as you would expect (Figure 4).

The second example uses a TL971 rail-to-rail-output voltage-follower circuit but with different results. In this case, the op amp receives a single 5V supply. From the datasheet specifications, the guaranteed $V_{ICMR}$ range spans 1.15 to 3.85V, or roughly 2.7V p-p centered at $V_{CC}/2$. A 1-kHz sine-wave input is applied with a dc offset of 2.5V. Adjust the amplitude of $V_{IN}$ from 200 mV p-p to larger levels until you see a change at $V_{OUT}$.

With $V_{IN}$ centered at 2.5V, $V_{IN}$ increases to 2.7V p-p with expected linear behavior at $V_{OUT}$. As $V_{IN}$ increases to approximately 3.5V p-p, centered at 2.5V, $V_{OUT}$ continues to follow $V_{IN}$ and exhibits proper op-amp behavior. Note that the linear behavior is better than what you might expect from the data-sheet limits for $V_{ICMR}$ but it still exceeds the guaranteed limits. As $V_{IN}$ increases slightly more to 3.52V p-p, $V_{OUT}$ starts to exhibit nonlinear behavior near both the positive, 5V, and negative, 0V, rails (Figure 5). $V_{IN}$ further increases to 4.2V p-p to clearly exceed $V_{ICMR}$. As the input peak exceeds the limit near the positive rail, the signal at $V_{OUT}$ rails out as it jumps up to the positive rail, 5V, and stays there until $V_{IN}$ returns to an acceptable range (Figure 6). As the input drops below the limit near the negative rail, the signal at $V_{OUT}$ exhibits a phase reversal as it jumps to midrail, 2.5V, and tracks $V_{IN}$ with an offset until $V_{IN}$ increases to an acceptable voltage within the $V_{ICMR}$. 

Figure 4 The TLC2272's $V_{OUT}$ shows clipping when $V_{IN}$ (Channel 1) exceeds 9.2V.

Figure 5 Nonlinear output behavior begins when the TL971's $V_{IN}$ is 3.52V p-p.
These examples show that different nonlinear behavior can result from different types of op amps when they exceed $V_{ICMR}$. Even though phase reversal results in the second case, note that phase reversals do not occur in every op amp that violates $V_{ICMR}$; it depends on the op amp.

The examples use an ac signal to evaluate $V_{ICMR}$ for an op-amp circuit. Another useful test is to apply a dc-voltage source to the input of the circuit in Figure 3. While varying the dc input, the output level behaves in a similar manner, except that it doesn’t vary over time. Depending on the type of circuit, ac analysis, dc analysis, or both may be useful in the early evaluation of the op amp.

**Overcoming a $V_{ICMR}$ issue**

What if you discover late in the design process that your op amp can’t meet the $V_{ICMR}$ requirements? The other device parameters may be ideal for your application, and it is difficult to change the device. You may want to consider one or more of the following options. First, if the input amplitude is too large, use a resistor divider to keep the signal within proper range of $V_{ICMR}$. Second, if the input signal offset is the problem, try using an input-biasing or dc-offset circuit to place the input signal within the specified $V_{ICMR}$ range for the op amp. Third, you could try changing the device to a rail-to-rail-input op amp that meets all of your other requirements.

When selecting an op amp, remember that input common-mode voltage range is among the most critical specifications to understand. If the device’s input cannot accept the levels or range of your input signal, you will likely experience problems at the output. Check this important detail first, and you’ll thank yourself later when your circuit is operating properly.

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**References**