INTRODUCTION

Current sense amplifiers are one of the specialty amplifiers from Analog Devices, Inc., used to amplify small differential signals in the presence of large common-mode voltages. A typical application for a current sense amplifier is amplifying the voltage across a shunt resistor. Analog Devices offers a variety of current sense amplifiers that operate with supply voltages as low as 1.8 V and withstand input common-mode voltages as high as 600 V.

Table 1. Supply Voltages and Input Common-Mode Voltages of Analog Devices Current Sense Amplifiers

<table>
<thead>
<tr>
<th>Part Number</th>
<th>$V_{\text{supply}}$</th>
<th>Min</th>
<th>Max</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD8293G80</td>
<td>1.8 V</td>
<td>5.5 V</td>
<td>1.8 V</td>
<td>5.5 V</td>
<td></td>
</tr>
<tr>
<td>AD626</td>
<td>2.4 V</td>
<td>10 V</td>
<td>-24 V</td>
<td>24 V</td>
<td></td>
</tr>
<tr>
<td>AD8274</td>
<td>2.5 V</td>
<td>18 V</td>
<td>-40.5 V</td>
<td>40.5 V</td>
<td></td>
</tr>
<tr>
<td>AD8279</td>
<td>4 V</td>
<td>36 V</td>
<td>-45.3 V</td>
<td>40.5 V</td>
<td></td>
</tr>
<tr>
<td>AD8210</td>
<td>4.5 V</td>
<td>5.5 V</td>
<td>-2 V</td>
<td>65 V</td>
<td></td>
</tr>
<tr>
<td>AD8207</td>
<td>4.5 V</td>
<td>5.5 V</td>
<td>-4 V</td>
<td>65 V</td>
<td></td>
</tr>
<tr>
<td>AD8418/AD8418A</td>
<td>2.7 V</td>
<td>5.5 V</td>
<td>-2 V</td>
<td>70 V</td>
<td></td>
</tr>
<tr>
<td>AD628</td>
<td>4.5 V</td>
<td>36 V</td>
<td>-120 V</td>
<td>120 V</td>
<td></td>
</tr>
<tr>
<td>AD629</td>
<td>5 V</td>
<td>36 V</td>
<td>-270 V</td>
<td>270 V</td>
<td></td>
</tr>
<tr>
<td>AD8479</td>
<td>5 V</td>
<td>36 V</td>
<td>-600 V</td>
<td>600 V</td>
<td></td>
</tr>
</tbody>
</table>

Many applications that utilize shunt resistors have common-mode voltages that vary as a function of time. Some examples of shunt applications with varying common-mode voltages are H bridge motor drivers, solenoid controllers, and dc-dc switching converters. In these applications, the common-mode voltages seen by the current sense amplifier vary, in PWM fashion, from a battery voltage to ground.

An ideal current sense amplifier does not react to the input common-mode variation. In practice, the current sense amplifier has a finite amount of common-mode rejection, typically specified at dc and in the order of 100 μV/V or 80 dB.

Table 2. CMRR of Analog Devices Current Sense Amplifiers

<table>
<thead>
<tr>
<th>Part Number</th>
<th>CMRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADA4830-1</td>
<td>65 dB</td>
</tr>
<tr>
<td>AD8270</td>
<td>76 dB</td>
</tr>
<tr>
<td>AD8210</td>
<td>80 dB</td>
</tr>
<tr>
<td>AD8207</td>
<td>80 dB</td>
</tr>
<tr>
<td>AD8203</td>
<td>82 dB</td>
</tr>
<tr>
<td>AD8418/AD8418A</td>
<td>86 dB</td>
</tr>
<tr>
<td>AD8207</td>
<td>90 dB</td>
</tr>
<tr>
<td>AD8210</td>
<td>100 dB</td>
</tr>
<tr>
<td>AD8211</td>
<td>120 dB</td>
</tr>
<tr>
<td>AD8293G80</td>
<td>140 dB</td>
</tr>
</tbody>
</table>

In addition to the output errors due to the dc common-mode rejection ratio (CMRR), there are errors associated with ac CMRR and the common-mode step response of the amplifier. This application note focuses on the common-mode step response of current sense amplifiers\(^1\).

\(^1\)Protected by U. S. Patent No. 8624668; other patents pending.
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REVISION HISTORY

6/14—Revision 0: Initial Version
COMMON-MODE STEP RESPONSE

Ideally, current sense amplifiers produce an output based on the difference of its inputs regardless of the actual values of the inputs (that is, common-mode voltage). However, in practice, the amplifier output may change at different common-mode levels of its input. The varying output with varying common-mode input is referred to as the common-mode step response.

The common-mode step response of the amplifier may be especially important in applications with large changes in the input common-mode voltage; while the amplifier is recovering from the change in input common-mode voltage, the output of the amplifier may not be valid due to the new offset induced by the new common-mode level. Thus, a long settling time of the amplifier (and thus the large error during that period) may seriously degrade the dynamic performance of the amplifier.

COMMON-MODE STEP RESPONSE MEASUREMENT

Very fast and accurate common-mode step response of current sense amplifiers is very challenging to achieve. It needs to have a very stable and fast source, fully shielded connectors, and a properly designed circuit. The basic functional block diagram used for this measurement is shown in Figure 1.

PWM Input

A PWM signal frequency of 0 Hz to 100 kHz is generated by a waveform generator and is used as the input signal of the MOSFET driver.

MOSFET Driver

This driver injects a high current to the MOSFETs in order to achieve very fast switching thus eliminating too much heat dissipation. The current provided by the driver is in the range of hundreds of milliamperes or even amperes.

MOSFET

The output of the driver is a positive voltage, thus N-channel power MOSFETs are used. These MOSFETs can tolerate a voltage as high as 100 V, and have typical rise and reverse recovery times of 35 ns and 115 ns respectively. In addition, these MOSFETs have an RON of 44 mΩ (which is enough to maintain the integrity of the signal) and can dissipate power as high as 130 W. The output of these MOSFETs serves as the common-mode input voltage (VCM) of the current sense amplifier.

Current Sense Amplifier

This amplifier amplifies the small differential signal in the presence of large common-mode voltage. The current sense amplifiers tested in this application note have common-mode voltages as high as +80 V and are powered with a single +5 V supply.

Common-Mode Step Response

The output of the current sense amplifier produces the common-mode step response waveform. This response may show a waveform with either a positive or negative peaking in the rising or falling edge depending on the dominancy of either the inverting or the noninverting input.

The simplified schematic diagram for the measurement of the common-mode step response is shown in Figure 2. The current sense amplifier modeled in this schematic diagram is the AD8210.
COMMON-MODE STEP RESPONSE RESULTS

Several Analog Devices current sense amplifiers configured in a shunt circuit were evaluated and compared to the most popular current sense amplifier from a competitor. The AD8210, the first current sense amplifier evaluated, is a single-supply bidirectional current sense amplifier which can tolerate a common-mode voltage of −2 V to +65 V. It has reference pins (V_{REF}) used to adjust the output offset and a fixed gain of 20.

The AD8207, a bidirectional difference amplifier configured as a current shunt amplifier, was also evaluated. It can resist a common-mode voltage of −4 V to +65 V for a +5 V supply and −4 V to +35 V for a +3.3 V supply. It also features a zero drift core that provides a typical offset drift less than 500 nV/°C and a gain drift typically below 10 ppm/°C. It also has a fixed gain of 20.

The AD8418 and AD8418A were also evaluated. These two current sense amplifiers feature a zero drift core that leads to a typical offset drift of 0.1 μV/°C throughout the operating temperature range and have common-mode voltage range of −2 V to +70 V. These two amplifiers are also fully qualified for automotive applications, include EMI filters, and patented circuitry to enable output accuracy with pulse-width modulation (PWM) type input common-mode voltages.

Figure 3 shows the comparison of the waveforms of the different Analog Devices current sense amplifiers with those of a competitor for an input common-mode voltage of +60 V.

COMMON-MODE STEP RESPONSE MEASUREMENT TECHNIQUES

To produce the accurate common-mode step response of a current sense amplifier, consider the connections, the components used, and the component placement.

Connections

Connector leads, such as in power supply, waveform generator, input, output, scope probes, and other interface connectors, should be as close as possible to the part or device under test (DUT) to avoid inducing or generating noise and interference in the wires.

Ground connections should meet at only one point, called single point ground, to avoid having different ground potentials in the system causing ground loop problems.

Instead of using the alligator clip for the ground of the scope probe, use a probe tip ground (like a coil of wire) and insert this in the probe. If this tip is unavailable, make a coil out of a solid or single-stranded wire then solder this next to the probing points (input and output pins of current sense amplifiers) to measure only the desired signal thus eliminating inductive noise which may cause unwanted ringing or peaking.
Figure 3. Common-Mode Step Response Measurement of Current Sense Amplifiers from Analog Devices and from a Competitor
Components Used
Bypass capacitors should be added in the power supplies to reduce the ripple voltage in a circuit and should never be taken for granted. Ceramic capacitors are good for this usage because of their high stability, high efficiency, and low loss.

Since the input common-mode voltage used in this application note is +60 V, the load resistor of the MOSFET driver should have a large power rating so that it can tolerate the high current flowing through it.

MOSFETs should have short reverse recovery time to minimize losses caused by often charging and discharging of the MOSFET diode.

Component Placement
Discrete devices comprising the MOSFET driver circuit, including the MOSFETs, and the current sense circuit should be placed as close as possible to the MOSFET driver to minimize ac impedance and to avoid noise or interference generated by long traces.

CONCLUSION
Analog Devices current sense amplifiers, as tested and verified, experience overshoot or undershoot of less than 700 mV. The competing product has almost 2 V overshoott. The Analog Devices current sense amplifiers described in this application note stabilized faster for both the rising and falling edges of the input common-mode voltage than the competing product.

In addition, these amplifiers actually reject very high input common-mode voltages of up to +60 V. With these advantages over the competing product, Analog Devices current sense amplifiers are very useful in preventing circuit faults, in preventing over-discharged batteries, and in maintaining the health of certain systems, such as battery monitors, power regulators, electric vehicles, generators, and motor controls.

FOR FURTHER INFORMATION
More information on the patent for improved common-mode step response for auto-zero amplifiers as listed and described on page 1 of this application note can be found online.

In addition, the following data sheet may be helpful:
- AD8210
- AD8207
- AD8418
- AD8418A