Application Note

Designing a Bootstrap Charge-Pump Power Supply for an Isolated Amplifier

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ABSTRACT

Isolated amplifiers provide isolation between their input signal and output signal, which is useful in many applications, such as phase current sensing in motor drives. Providing the high-side power to an isolated amplifier can be challenging. This application note introduces a bootstrap charge-pump circuit as a small, low-cost alternative for generating the high-side power supply and goes into detail regarding the design of such a circuit.

Table of Contents

List of Figures

List of Tables

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1 Introduction

Isolated amplifiers can measure voltage or current with relatively high accuracy while keeping the measurements isolated from the low-side. This is useful in applications where the high-side voltage requires isolation for safety-related concerns, or when the high-side can experience sudden transients which can damage a controller on the low-side. Common applications include measuring a high-voltage motor bus or measuring motor phase current.

However, isolated amplifiers require the high-side power supply to be isolated from the low-side power supply, which can lead to increased size and complexity. One alternative is a transformer-isolated power supply, which produces the high-side rail from the low-side while keeping the high-side isolated from the low-side. However, transformers can be large and costly. A bootstrap charge-pump power supply is a cost-effective alternative. The power is supplied from a pulse-width modulation (PWM) signal, and only requires a capacitor, a diode, and a current-limiting resistor. In some cases, a linear dropout regulator (LDO) can be required as well.

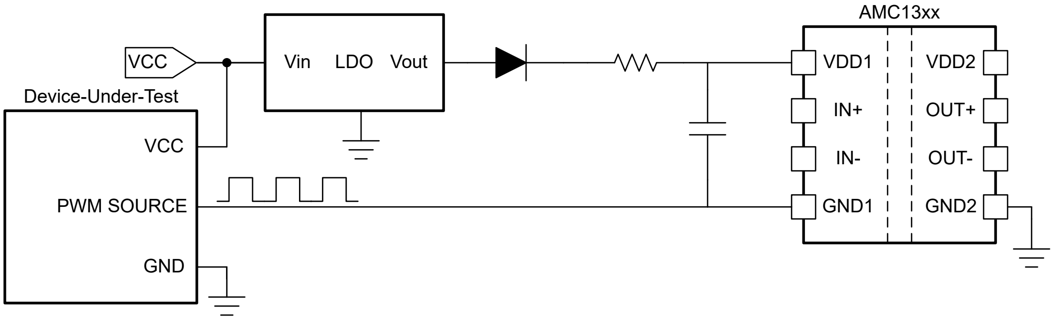

Figure 1-1. Bootstrap Power Supply

2 Bootstrap Power Supply Design

The bootstrap operates from an input voltage and a PWM signal. The input voltage is supplied from the same supply powering the device-under-test (DUT), and the input voltage can be stepped down using an LDO. Since the bootstrap requires a PWM signal to operate, the signal can only be used with DUTs which produce or operate with a PWM signal. The DUT is not necessarily isolated from the low-side of the amplifier, as shown in Figure 1-1, which is why a DC-DC power converter alone cannot be used. The high-side of the amplifier does not share a ground connection with the DUT. The PWM signal is tied to the isolated amplifier's high-side ground. The bootstrap make sure the high-side power supply always floats above the PWM signal, so the high-side power supply has a steady signal, even though the high-side ground is a PWM signal.

The input voltage to the bootstrap circuit determines the output steady state value, so the input voltage must be close to the desired high-side supply voltage to avoid violating the amplifier’s high-side supply specifications. An LDO is required if the DUT VCC bus is outside of the isolated amplifier's recommended operating conditions. LDOs generally require few additional external components, and LDOs produce cleaner signals than switching regulators, which is why LDOs are recommended in this application. The input voltage to the bootstrap circuit is greater than the DUT ground, so when the PWM signal is low, there is a positive voltage drop across the diode, and it conducts, charging the capacitor, as shown in Figure 2-1.

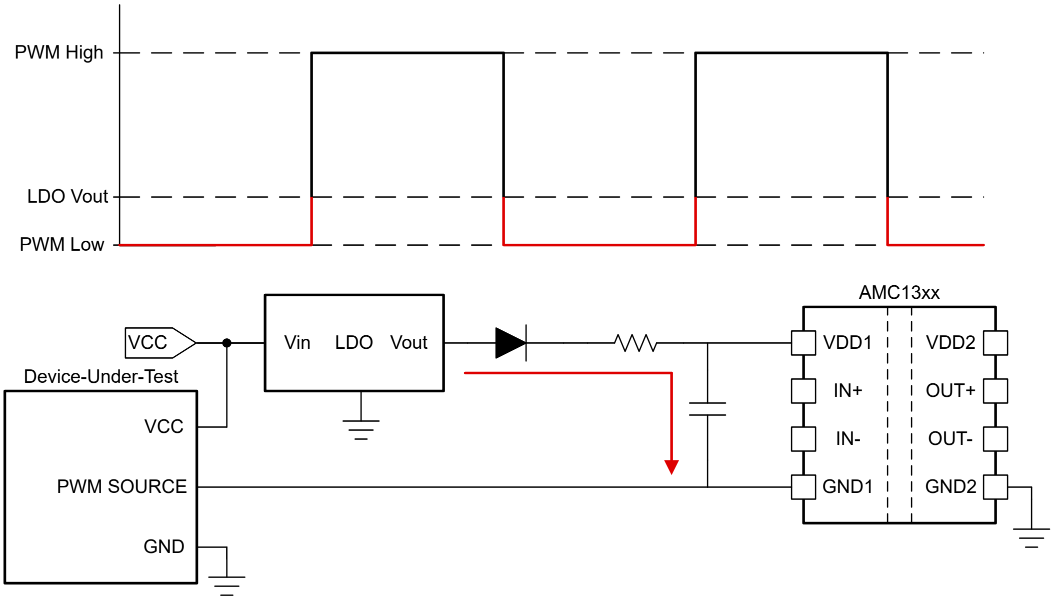

Figure 2-1. Charging the Bootstrap Capacitor

When the PWM signal is high, there is no voltage drop or a negative voltage drop across the capacitor, and the signal stops conducting, so the capacitor discharges into the high-side supply, as shown in Figure 2-2. The bootstrap circuit can achieve steady state when the amount of voltage stored by the capacitor when the PWM signal is low is equal to the amount of voltage discharged by the capacitor when the PWM signal is high. This means that the start-up time and steady state ripple are dependent on the RC time constant and can be impacted by the frequency and duty cycle of the PWM signal.

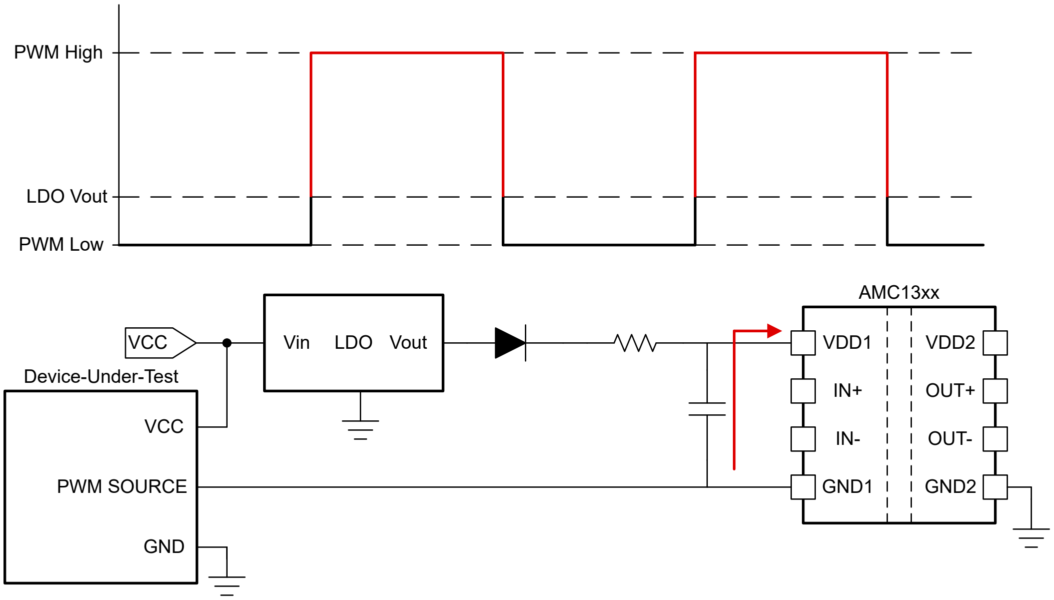

Figure 2-2. Discharging the Bootstrap Capacitor

2.1 Selection of Charge Pump Capacitor

The maximum value supplied by the bootstrap can be approximated by taking the input supply to the bootstrap and subtracting the voltage drop of the diode. However, the bootstrap can reach steady state before the bootstrap reaches the maximum value, depending on the value of the RC circuit and the PWM signal. The RC time constant is defined as:

$$\tau = \mathrm{R} \times \mathrm{C} \tag{1}$$

The capacitor and resistor determine the RC time constant for charging and discharging the capacitor. There is a trade-off between start-up time and steady-state ripple. A smaller time constant means that the capacitor can charge and discharge more quickly, reaching steady-state sooner. However, once the capacitor reaches steady-state, the capacitor can charge or discharge more voltage per PWM duty cycle than the capacitor can with a larger time constant, which leads to larger ripple. Likewise, a larger time constant can result in less ripple due to longer charge or discharge times. The capacitor value can be estimated using the following parameters:

1. PWM switching frequency
2. PWM duty cycle
3. Current required to power the isolated amplifier
4. Allowable ripple

We can rearrange Equation 2 as shown in Equation 3 to solve for capacitance.

$$\mathrm{Q} = \mathrm{I} \times \mathrm{t} = \Delta \mathrm{V}_{\mathrm{ripple}} \times \mathrm{C} \tag{2}$$

$$\mathrm{C} = \frac{\mathrm{I} \times \mathrm{t}}{\Delta \mathrm{V}_{\mathrm{ripple}}} \tag{3}$$

Assuming a 20 kHz switching frequency with a 50% duty cycle, using the maximum current draw from the AMC1311-Q1 data sheet, and mandating a 100 mV maximum ripple requirement, the following minimum capacitance value is received:

$$\mathrm{C} = \frac{9.7\mathrm{mA} \times 0.5 \times \frac{1}{20\mathrm{kHz}}}{100\mathrm{mV}} = 2.4\mu\mathrm{F} \tag{4}$$

From there, the bootstrap can be simulated to estimate start-up time, and an appropriate capacitor and resistor can be selected based on the start-up time requirements. The resistor needs to be selected so the resistor does not prevent the high-side of the amplifier from drawing sufficient current.

2.2 Simulation in TINA-TI

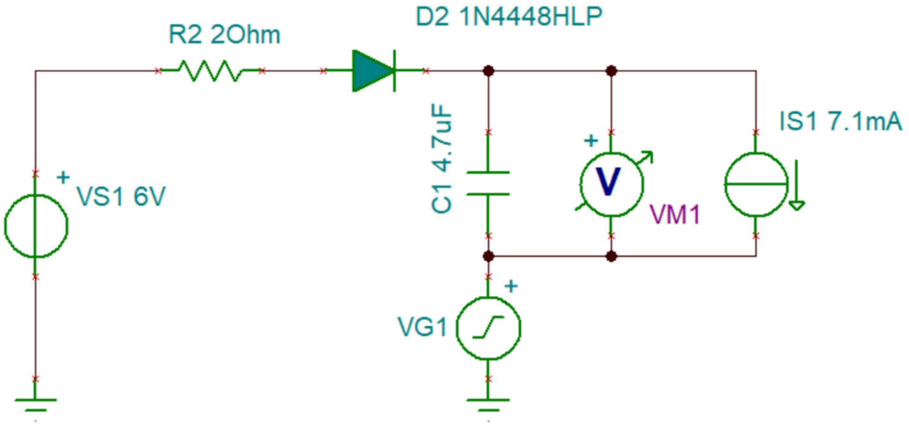

Figure 2-3. Simulation Model

VS1 is the output from the LDO, VG1 is used to simulate the PWM signal, and IS1 simulates the load draw from the isolated amplifier. Since VS1 is 6 V and the voltage drop across the diode is 300 mV, the maximum output of the bootstrap is 5.4 V. VG1 is sourcing a 20 kHz, 50 V_{pp} PWM signal with a duty cycle of 50%. C1 is stepped through four different capacitor values.

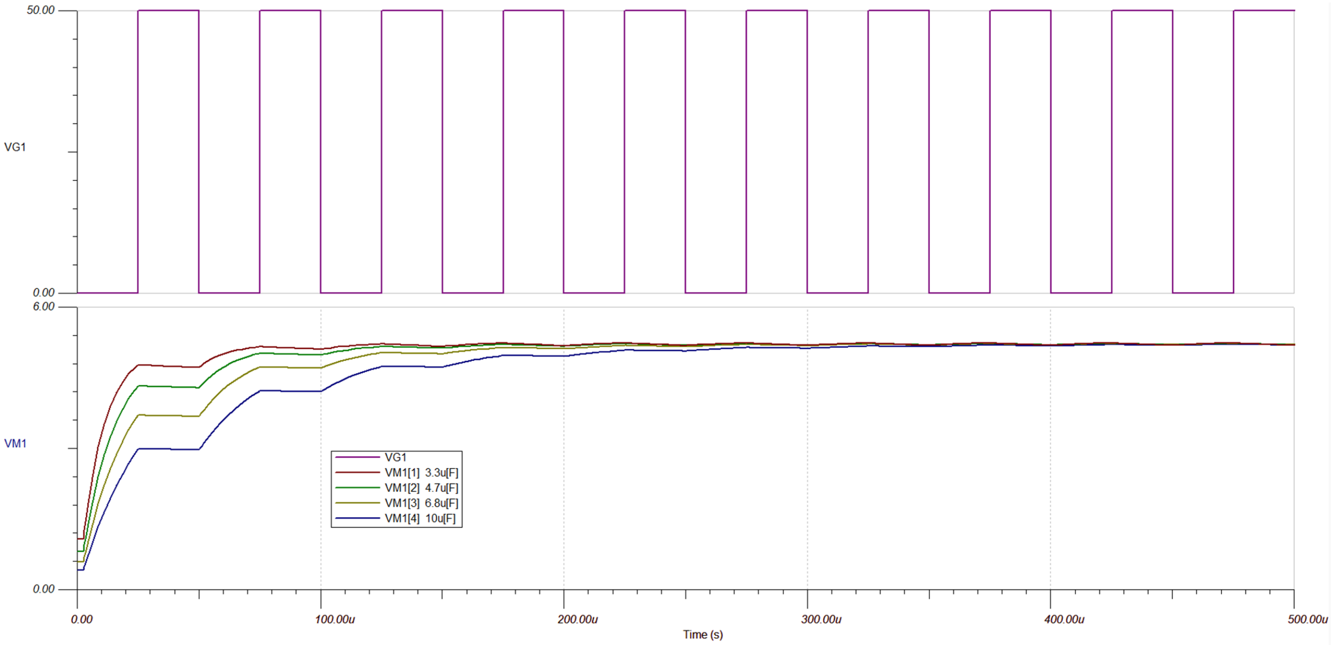

Figure 2-4. Comparing Capacitor Values

Table 2-1. Steady State Output Voltage with Different Capacitors

Capacitor Value (µF)	Steady State Ripple (mV)	Average Steady State Value (V)
3.3	53.6	5.215
4.7	37.7	5.200
6.8	25.8	5.215
10	17.7	5.215

Figure 2-4 shows four different capacitor values with the same PWM signal. Table 2-1 shows the steady state output voltage with the different capacitors. Notice that none of the capacitors reach the theoretical maximum steady state value of 5.4 V. However, as the ripple decreases, the start-up time clearly increases. The signal with 4.7 µF has a good balance between start-up time and ripple.

The start-up time and the steady state ripple of the bootstrap circuit also depends on the frequency and duty cycle of the input PWM signal. We can observe this in simulation by setting C1 to a single value and changing the PWM signal generated by VG1.

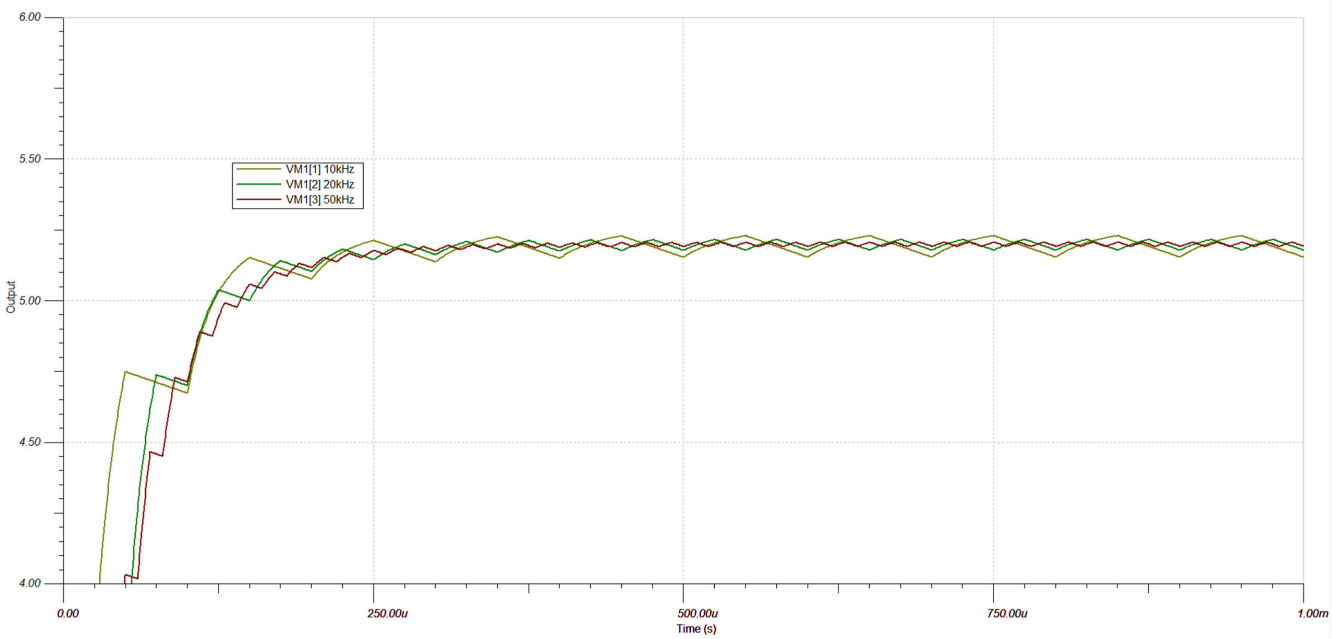

Figure 2-5. Change PWM Frequency

Table 2-2. Start-Up Time and Steady State Voltage for Different Frequencies

PWM Frequency (kHz)	Steady State Ripple (mV)	Average Steady State Value (V)
10	75.1	5.190
20	37.7	5.200
50	14.7	5.200

C1 is 4.7 µF, and the PWM signal has an amplitude of 50 V_{pp} and a 50% duty cycle. The frequency has a much bigger impact on the output ripple without affecting the start-up time and average steady state too dramatically, as shown in Table 2-2.

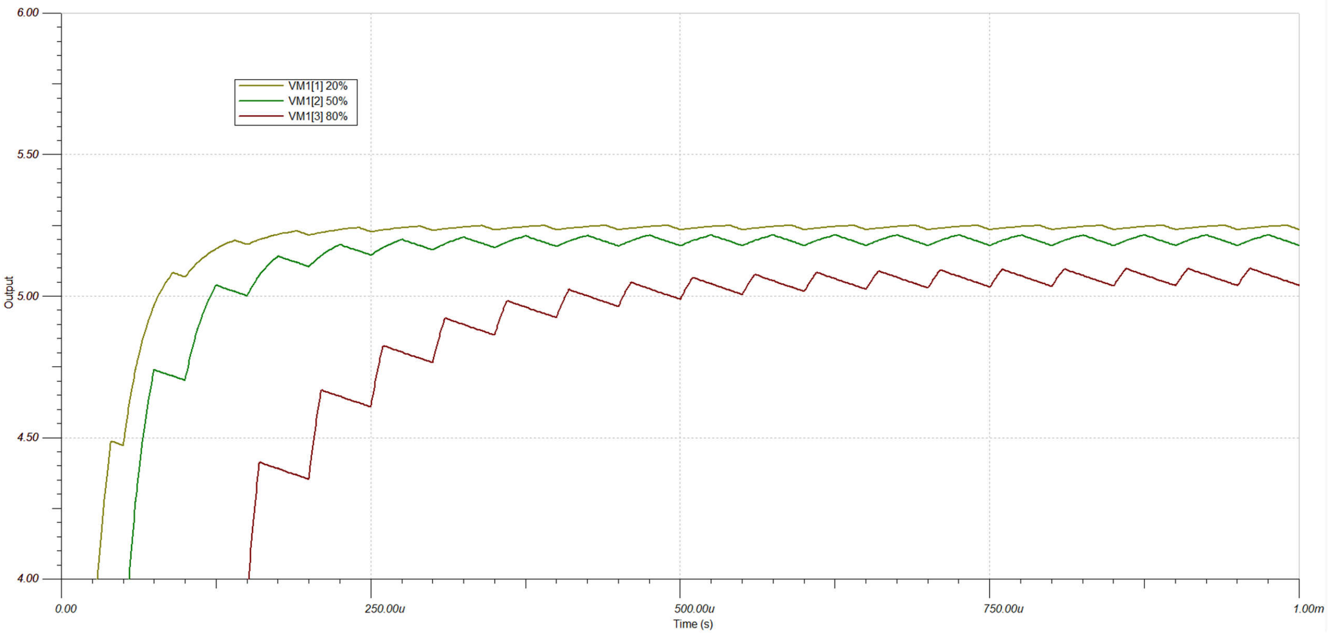

Figure 2-6. Change PWM Duty Cycle

Table 2-3. Start-Up Time and Steady State Voltage for Different Duty Cycles

PWM Duty Cycle	Steady State Ripple (mV)	Average Steady State Value (V)
20%	14.7	5.245
50%	37.7	5.200
80%	59.9	5.070

C1 is 4.7 µF and the PWM signal has an amplitude of 50 V_{pp} and a 20 kHz frequency. The start-up time and average output are impacted much more, as shown in Figure 2-6 and Table 2-3.

Too much ripple can impact the performance of the isolated amplifier as the bouncing power supply can cause common-mode errors on the output. However, the isolated amplifier cannot be verified to measure the DUT accurately until the amplifier has reached the minimum recommended value for the amplifier's high-side power supply. Knowing the expected PWM output signal is crucial to designing an effective bootstrap circuit within the system's parameters. However, the 4.7 µF capacitor was selected under the assumption that the PWM signal can have a duty cycle of 50% and have a 20 kHz frequency (see Section 2.1), so the minimum capacitance can be adjusted based on the PWM signal characteristics (see Equation 4).

2.3 Hardware Test with AMC1311-Q1

The actual circuit is built as Figure 1-1 to verify the simulations. C=4.7 μF, R=2 Ω, the output of the LDO is 6 V, and the input PWM signal is 50 V_{pp} at 20 kHz with a 50% duty cycle. AMC1311-Q1 is the selected isolated amplifier and TPS7A4101 is the selected LDO for the wide input range.

The start-up time is around 260 μs, and the steady-state output is 5.1 V with 29.7 mV ripple, matching reasonably well with the Figure 2-3. The discrepancy between simulation and hardware is due to equipment current limitations, which are not accounted for in an designed for simulation.

The ripple from the bootstrap power supply had minimal impact on the performance of AMC1311-Q1 when compared to the performance with a clean power supply. The clean signal was generated using a transformer and an LDO from the low-side power rail. This transformer power supply is approximately twice the size of the bootstrap power supply and much more expensive than the bootstrap, due to the cost of the transformer. If the ripple was too high, the bootstrap power supply can also be smoothed with simple RC filters. This can add minimal size and cost to the circuit.

3 Summary

A charge-pump bootstrap circuit is an effective way to produce an isolated power rail for an isolated amplifier in PWM applications. A well-designed boostrap power supply can operate just as effectively as a clean power supply, while saving space and cost.

There are several key factors to consider when designing a bootstrap circuit. It is important to know the current draw of the isolated amplifier, the frequency and duty cycle of the PWM signal, the allowable range for circuit start-up time, and the allowable power supply ripple for the isolated amplifier. All of these specifications can affect the selection of the RC circuit used in the bootstrap circuit. A bootstrap can be simulated easily, making the selection process much simpler since the designer can easily test various RC values under different circuit conditions.

4 Reference

1. Texas Instruments, *AMC13xx Parametric Table*.
2. Texas Instruments, *DC+ Bus Power-Supply Solution Using Bootstrap Charge Pump Technique* application note.
3. Texas Instruments, *Using Isolated Comparators for Fault Detection in Electric Motor Drives* analog design journal.
4. Texas Instruments, *Design Considerations for Isolated Current Sensing* analog design journal.

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