Analog Engineer's Circuit

# Isolated Current-Sensing Circuit With Front-End Gain Stage

TEXAS INSTRUMENTS

Data Converters

Design Goals

Current Source (Nominal)		Current Source (Short)	Input Voltage		Output Voltage	Power Supplies	
$I_{IN\ MIN}$	$I_{IN\ MAX}$	I_{SHORT}	$V_{SHUNT,\ MIN}$	$V_{SHUNT,\ MAX}$	V_{OUT}	V_{DD1}	V_{DD2}
±10 mA	±10 A	±200 A	±10 µV	±10 mV	55 mV – 3.245 V	5 V	3.3 V

Design Description

Some applications require a circuit to measure small nominal currents while withstanding a high short-circuit current, such as a circuit breaker. This circuit design document describes an isolated current-sensing circuit that can accurately measure nominal load currents from ±10 mA to ±10 A, while withstanding a short-circuit current up to ±200 A. For the purposes of this circuit, assume the output is used with a 3.3-V single-ended ADC, such as one that can be found integrated into an MSP430. The isolation between the line current being measured and the ADC is achieved using an isolated amplifier (AMC1302). With a 1-mΩ shunt resistor, the expected minimum nominal current produces a ±10-µV signal, a signal which is too small to resolve accurately near a zero voltage input due to the delta-sigma modulator dead zone. To remedy this, the circuit uses a 2-channel operational amplifier (TLV9002) to both amplify the signal by a gain of 5 V/V and set the common-mode voltage to 1 V; this not only brings the minimum nominal current out of the dead zone, but also brings the maximum nominal current up to match the full-scale linear input range of the isolated amplifier. The full-scale linear input range of the isolated amplifier is ±50 mV, with a differential output swing of ±2.05 V, on an output common-mode voltage of 1.44 V and a fixed internal gain of 41 V/V. On the output side of the isolated amplifier, a second 2-channel operational amplifier (TLV9002) is used, where: the first channel is used to set the single-ended common-mode voltage to 1.65 V and the second channel transforms the differential output signal from the isolated amplifier into a single-ended that can be used with a 3.3-V single-ended ADC.
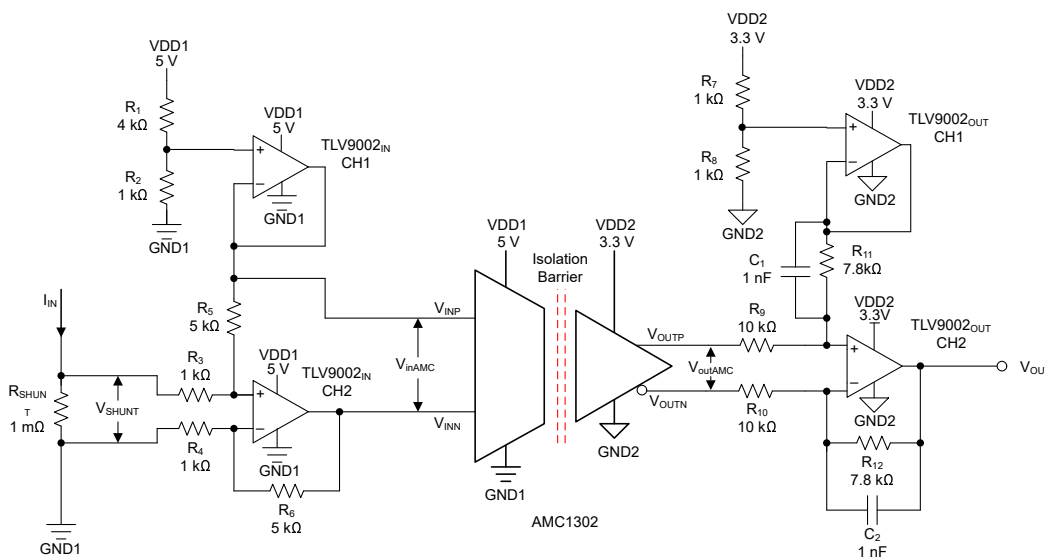
Design Notes

1. The AMC1302 was selected as the isolated amplifier due to the low power consumption, resolution, and ±50-mV full-scale input voltage range of the amplifier.
2. The TLV9002 was selected as the operational amplifier for the low cost, low offset, small size, and dual-channel package.
3. Select a low impedance, low-noise source for both VDD1 and VDD2 which provide supply for the TLV9002$_{IN}$, TLV9002$_{OUT}$, and AMC1302; while also being used to set the common-mode voltage for the single-ended output.
   - VDD1 is referenced to GND1 and VDD2 is referenced to GND2.
4. For the highest accuracy, use a precision shunt resistor with a low temperature coefficient.
5. Select the shunt resistor for expected nominal and short-circuit input current levels.
   a. For continuous operation, do not run the shunt resistors at more than two-thirds the rated current under normal conditions as per IEEE standards. Further reducing the shunt resistance or increasing the rated wattage can be necessary for applications with stringent power dissipation requirements.
   b. For short-circuit current, check the short-term overload specification in the shunt resistor data sheet. The current is often 5 × the nominal power dissipation.
   c. For assistance with calculating the power dissipation, see the Isolated Amplifier Current Sensing Excel Calculator.
6. Use the proper resistor divider values to set the common-mode voltage on channel 1 of both the TLV9002$_{IN}$ and TLV9002$_{OUT}$. Make sure the input common-mode specification of the isolated amplifier is not violated.
7. Select the proper values for the gain setting resistors on channel 2 of the TLV9002$_{OUT}$ so that the single-ended output has an appropriate output swing.

Design Steps

1. Determine the appropriate shunt resistor value based on the maximum nominal current.

$$R_{SHUNT} = \frac{V_{inMax}}{I_{inMax}} = \frac{50\ mV}{10\ A} = 5\ m\Omega$$

2. Since this shunt resistor must be able to withstand a 200-A short-circuit current, further reduce the shunt resistor resistance by a factor of 5 which is compensated for in step 6. Determine the shunt resistor power dissipation during maximum nominal current operation.

$$Power\ R_{SHUNT} = I_{inMax}^2 \times R_{SHUNT} = 100\ A^2 \times 1\ m\Omega = 0.1\ W$$

Determine the shunt resistor power dissipation during minimum nominal current operation.

$$Power\ R_{SHUNT} = I_{inMin}^2 \times R_{SHUNT} = 0.1\ mA^2 \times 1\ m\Omega = 0.1\ \mu W$$

3. Determine the shunt resistor power dissipation during short circuit. Be sure to verify that the selected short-term overload specification (typically 5 × nominal) is capable of withstanding the power dissipated by the short circuit.

$$Power\ R_{SHUNT} = I_{inShort}^2 \times R_{SHUNT} = 40,000\ A^2 \times 1\ m\Omega = 40\ W$$

Select a shunt resistor with power dissipation reduced by a factor of 5. So, if the short-term overload requirement is 40 W, shunt P$_{dissipation}$ = 8 W. For more details, see the *Design considerations for isolated current sensing* analog design journal.

4. Channel 1 of the TLV9002$_{IN}$ is used to set the 1-V common-mode voltage of the single-ended output of channel 2 of the TLV9002$_{IN}$. The 1-V output of channel 1 is also sent to the positive input of the AMC1302. With a 5-V supply, a simple resistor divider can be used to divide 5 V down to 1 V. Using 4 kΩ for R$_1$, R$_2$ can be calculated using the following equation.

$$R_2 = \frac{V_{CM} \times R_1}{V_{DD} - V_{CM}} = \frac{1.00\ V \times 4000\ \Omega}{5.00\ V - 1.00\ V} = 1000\ \Omega$$

5. Channel 2 of the TLV9002$_{IN}$ is used to amplify the voltage from the shunt resistor such that the full-scale input voltage range of the AMC1302 is utilized when measuring the maximum nominal current range. With a shunt resistor of 1 mΩ and a maximum nominal current of ±10 A, the output voltage from the shunt resistor is ±10 mV. Since the maximum input voltage of the AMC1302 is ±50 mV, the output of the shunt resistor must be amplified by 5 V/V. While keeping R3|R4 at 1 kΩ, the resistor value of R5|R6 can be found with the following equation.

$$Gain\left(V/V\right) = \frac{R_{5,6}}{R_{3,4}}; \; R_{5,6} = Gain\left(V/V\right) \times R_{3,4} = 5\,V/V \times 1\,k\Omega = 5\,k\Omega$$

6. Verify the absolute maximum voltage limits of the input of the AMC1302 are not violated during a short-circuit based on the chosen shunt resistor. A 200-A short-circuit current results in a 1-V differential voltage being applied to the AMC1302. Since the input common mode is set to 1 V, a maximum of 2 V is applied to the negative input of the AMC1302 with respect to GND1.

$$V_{inAMC} = 200\,A \times 0.001\,\Omega \times 5\,V/V = 1\,V$$

The absolute maximum input voltage for the AMC1302 is 500 mV greater than the high-side supply voltage (as stated in the *AMC1302 Precision, ±50-mV Input, Reinforced Isolated Amplifier* data sheet). With a 5-V high-side supply voltage, the absolute maximum input voltage rating is not violated.

7. Channel 1 of the TLV9002$_{OUT}$ is used to set the 1.65-V common-mode voltage of the single-ended output of channel 2 of TLV9002$_{OUT}$. With a 3.3-V supply, a simple resistor divider can be used to divide 3.3 V down to 1.65 V. Using 1 kΩ for R$_7$, R$_8$ can be calculated using the following equation.

$$R_8 = \frac{V_{CM} \times R_7}{V_{DD} - V_{CM}} = \frac{1.65\,V \times 1000\,\Omega}{3.3\,V - 1.65\,V} = 1000\,\Omega$$

8. While the TLV9002 is a rail-to-rail operational amplifier, the output of a TLV9002 can only swing a maximum of 55 mV from the supply rails. Due to this, the single-ended output of TLV9002$_{OUT}$ can swing from 55 mV to 3.245 V (3.19 V$_{pk-pk}$).

9. The V$_{OUTP}$ and V$_{OUTN}$ outputs of the AMC1302 are 2.05 V$_{pk-pk}$, 180 degrees out of phase, and have a common-mode voltage of 1.44 V. Therefore, the differential output is ±2.05 V or 4.1 V$_{pk-pk}$.

To stay within the output limitations of TLV9002$_{OUT}$, the output of the AMC1302 needs to be attenuated by a factor of 3.2 / 4.1. When R$_9$ = R$_{10}$ and R$_{11}$ = R$_{12}$, the following transfer function for the differential to single-ended stage can be used to calculate R$_{11}$ and R$_{12}$.

$$V_{OUT} = (V_{OUTP} - V_{OUTN}) \times \left(\frac{R_{11,12}}{R_{9,10}}\right) + V_{CM}$$

10. Using the previously-calculated output swing of the TLV9002$_{OUT}$ and setting R$_9$ and R$_{10}$ to be 10 kΩ, R$_{11}$ and R$_{12}$ can be calculated to be 7.8 kΩ using the following equation.

$$3.2 = (2.465\,V - 415\,mV) \times \left(\frac{R_{11,12}}{10\,k\Omega}\right) + 1.65$$

Using standard 0.1% resistor values, a 7.8 kΩ resistor can be used. This provides the maximum output swing within the limitations of the TLV9002.

11. Capacitors C$_1$ and C$_2$ are placed in parallel to resistors R$_{11}$ and R$_{12}$ to limit high-frequency signals. When R$_{11}$ = R$_{12}$ and C$_1$ = C$_2$, the cutoff frequency can be calculated using the following equation.

$$f_c = \frac{1}{2 \times \pi \times R_{11,12} \times C_{1,2}}$$

When the C$_1$ = C$_2$ = 1 nF and R$_{11}$ = R$_{12}$ = 7800 Ω, the cutoff frequency can be calculated to be 20.414 kHz.

$$f_c = \frac{1}{2 \times \pi \times 7800\,\Omega \times 1\,nF} = 20.414\,kHz$$

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Design Simulations

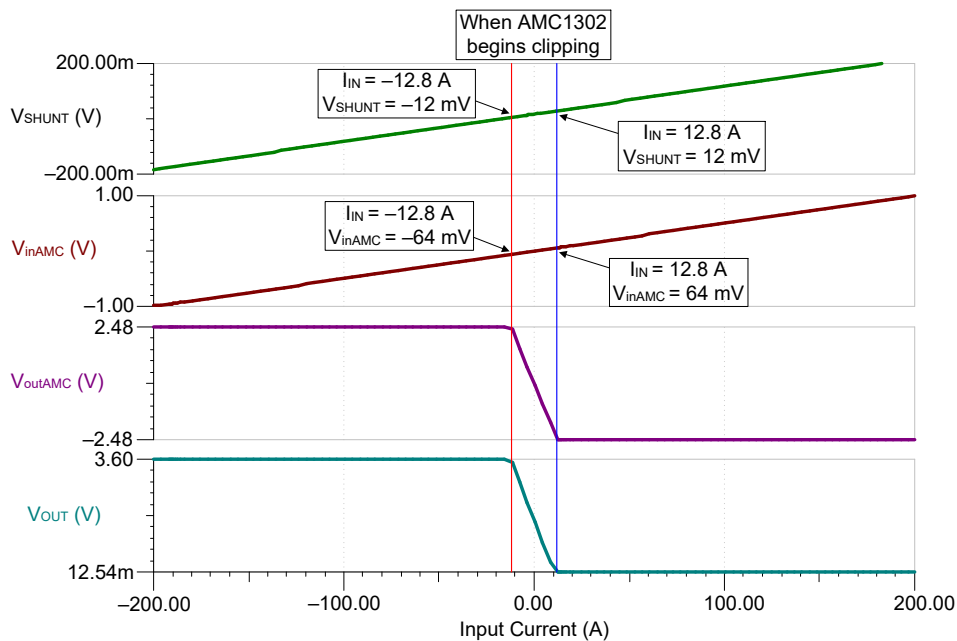### DC Simulation Results

Simulation Results shows the simulated DC characteristics of the voltage across the shunt, the differential input/output of the AMC1302, and the single-ended output of the TLV9002 amplifier from –10 A to 10 A.
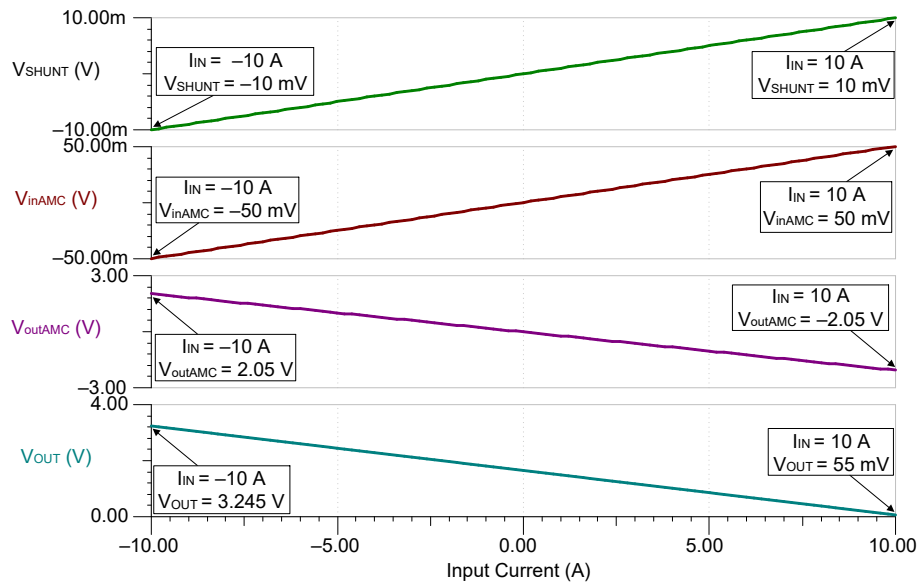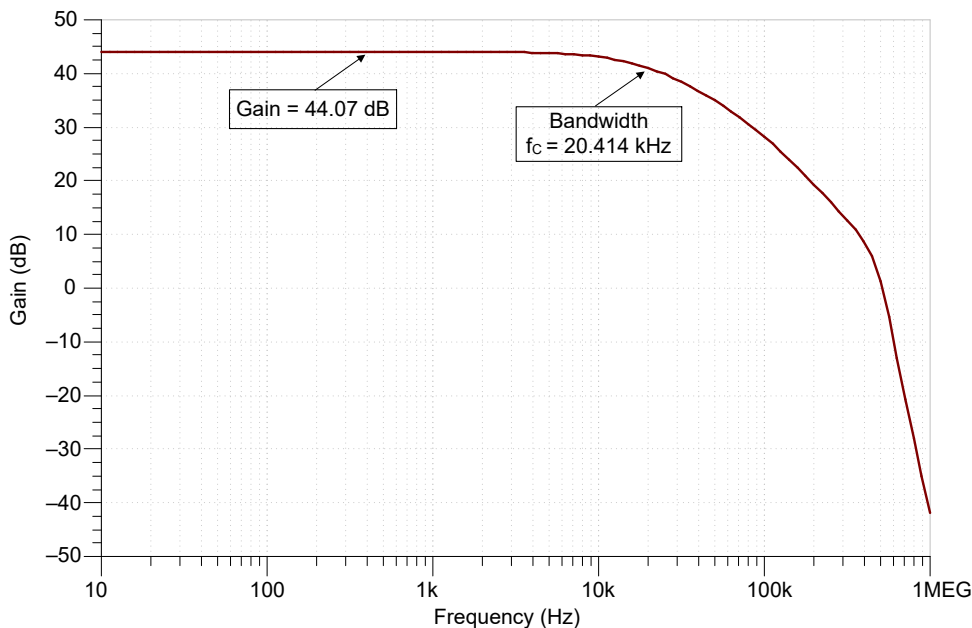

Simulation Results

Short-Circuit Event Simulation shows a simulation of the circuit during a short-circuit event by demonstrating how the inputs and outputs react at ±200 A. The red and blue lines going through the graphs mark the points where the output of the AMC1302 begins clipping. From that point on, the purpose of the circuit is to continue operating after the short-circuit event. In the *Design Steps* section, the values of the gain and shunt-resistance on the high-side of the AMC1302 were chosen to avoid damage during this event. The following simulation validates those choices: the maximum input voltage entering the AMC1302 at the short-circuit event is ±1 V, which is lower than the absolute maximum ratings of the part. Therefore, the simulation confirms that the circuit continues operation after the short-circuit event passes.

Short-Circuit Event Simulation

Closed-Loop AC Simulation Results

AC Simulation shows the AC transfer characteristics of the single-ended output. This simulation shows what gain (dB) to expect as the frequency approaches and surpasses the cutoff that is calculated with the second equation in step 11. The analog front end has a gain of 5 V/V, the AMC1302 has a gain of 41 V/V, and the differential-to-single-ended conversion has a gain of 0.78 V/V; thus a gain of 44.07 dB is expected, which is illustrated in the following figure.

AC Simulation

Sine-Wave Simulation Results

Sine-Wave Simulation shows the output of the shunt, the differential input and output of the AMC1302, and the single-ended output of the TLV9002 in response to a sine wave with an amplitude from –10 A to 10 A. The differential output of the AMC1302 is ±2.05 V_{pk-pk} as expected, and the single-ended output is 3.19 V_{pk-pk} and swings from 55 mV to 3.245 V.
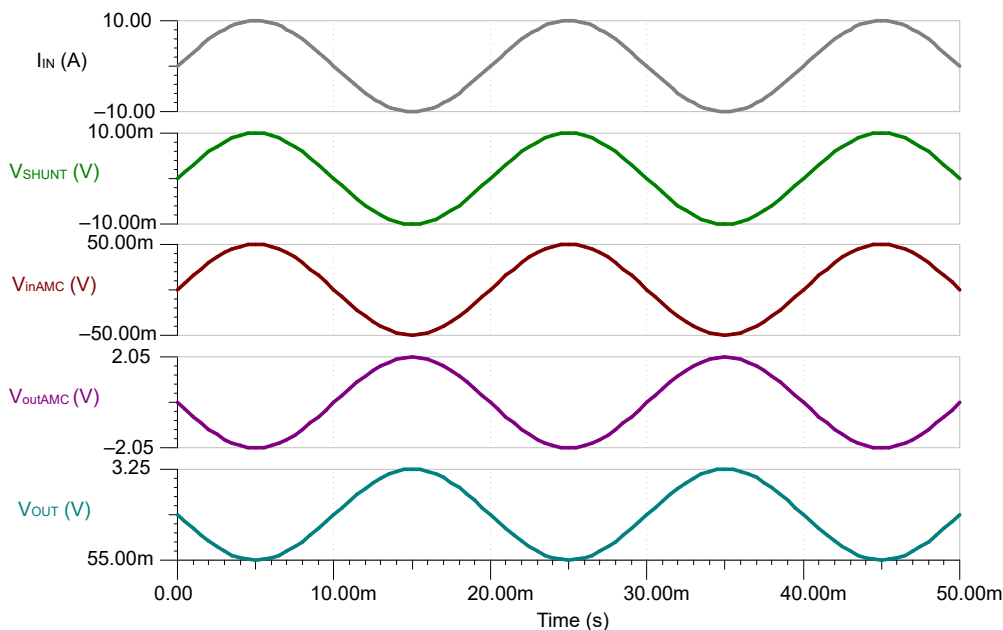
Sine-Wave Simulation

Design References

See the *Analog Engineer's Circuit Cookbooks* for TI's comprehensive circuit library and the *Interfacing a Differential-Output (Isolated) Amp to a Single-Ended Input ADC* application brief for more information on the differential to single-ended output conversion.

Design Featured Isolated Amplifier

AMC1302	
Working Voltage	1500 V$_{RMS}$
Gain	41 V/V
Bandwidth	280 kHz TYP
Linear Input Voltage Range	±50 mV
Input Resistance	4.9 kΩ (typ)
Input Offset Voltage and Drift	±50 µV (max), ±0.8 µV/°C (max)
Gain Error and Drift	±0.2% (max), ±35 ppm/°C (max)
Nonlinearity and Drift	0.03% (max), 1 ppm/°C (typ)
Isolation Transient Overvoltage	7071 V$_{PEAK}$
Common-Mode Transient Immunity, CMTI	100 kV/µs (min)

Design Alternate Isolated Amplifier

AMC3302	
Working Voltage	1200 V$_{RMS}$
Gain	41 V/V
Bandwidth	334 kHz TYP
Linear Input Voltage Range	±50 mV
Input Resistance	4.9 kΩ (typ)
Input Offset Voltage and Drift	±50 µV (max), ±0.5 µV/°C (max)
Gain Error and Drift	±0.2% (max), ±35 ppm/°C (max)
Nonlinearity and Drift	±0.03% (max), 1 ppm/°C (typ)
Isolation Transient Overvoltage	6000 V$_{PEAK}$
Common-Mode Transient Immunity, CMTI	95 kV/us (min)

AMC1202	
Working Voltage	1000 V$_{RMS}$
Gain	41 V/V
Bandwidth	280 kHz TYP
Linear Input Voltage Range	±50 mV
Input Resistance	4.9 kΩ (typ)
Input Offset Voltage and Drift	±50 µV (max), ±0.8 µV/°C (max)
Gain Error and Drift	±0.2% (max), ±35 ppm/°C (max)
Nonlinearity and Drift	±0.03% (max), 1 ppm/°C (typ)
Isolation Transient Overvoltage	4250 V$_{PEAK}$
Common-Mode Transient Immunity, CMTI	100 kV/µs (min)

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