High-current battery monitor circuit: 0–10A, 0–10kHz, 18 bit

Luis Chioye

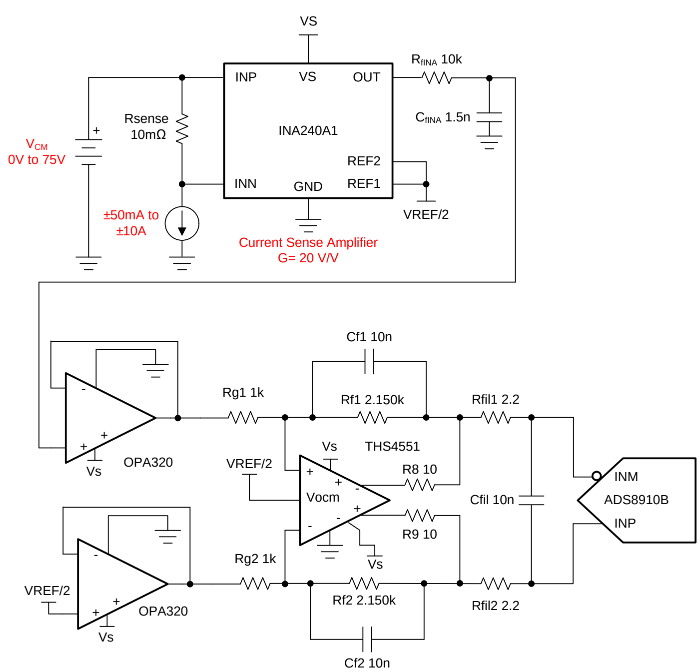
Sense Resistor Current	INA Out, Amplifier Input	ADC Input	Digital Output ADS8910B
MinCurrent = ±50mA	Out = ±10mV	VoutDif = ±21.3mV	233_H 563_{10}, $3FDCB_H$ -564_0
MaxCurrent = +10A	Out = ±2V	VoutDif = ± 4.3V	$1B851^H$ 112722_{10} $247AE_H$ -112722_{10}

Supply and Reference			
Vs	Vee	Vref	Vcm
5.3 V <Vs <5.5V	0V	5V	2.5V

Design Description

This single-supply current sensing solution can measure a current signal in the range of ±50 mA to ±10 A across a shunt resistor. The current sense amplifier can measure shunt resistors over a wide common-mode voltage range from 0V to 75V. A fully differential amplifier (FDA) performs the single-ended to differential conversion and drives the SAR ADC differential input scale of ±5V at full data rate of 1MSPS. The values in the *component selection* section can be adjusted to allow for different current levels.

This circuit implementation is applicable in accurate voltage measurement applications such as Battery Maintenance Systems, Battery Analyzers, *Battery Testing Equipment*, *ATE*, and Remote Radio Units (RRU) in wireless base stations.



Specifications:

Error Analysis	Calculated	Simulated	Measured
Transient ADC Input Settling	> 1LSB > 38µV	6.6µV	N/A
Noise (at ADC Input)	221.8µV rms	207.3µV rms	227µV rms
Bandwidth	10.6kHz	10.71kHz	10.71kHz

Design Notes

1. Determine the shunt sense resistor value and select the current sense amplifier based on the input current range and input common mode voltage requirements. This is covered in the *component selection* section.
2. Determine the fully differential amplifier gain based on the current sense amplifier output, the ADC full-scale range input and the output swing specifications of the fully differential amplifier. This is covered in the *component selection* section.
3. Select COG capacitors to minimize distortion.
4. Use 0.1% 20ppm/°C film resistors or better for good accuracy, low gain drift, and to minimize distortion.
5. The TI Precision Labs training video series covers methods for error analysis. Review the following links for methods to minimize gain, offset, drift, and noise errors: *Error and Noise*.
6. The *TI Precision Labs – ADCs* training video series covers methods for selecting the charge bucket circuit R_{filt} and C_{filt}. These component values are dependent on the amplifier bandwidth, data converter sampling rate, and data converter design. The values shown here will give good settling and ac performance for the amplifier, gain settings, and data converter in this example. If the design is modified, select a different RC filter. Refer to *Introduction to SAR ADC Front-End Component Selection* for an explanation of how to select the RC filter for best settling and ac performance.

Component Selection for Current Sense Circuit

1. Choose the Rsense resistor and find the gain for the current sense amplifier (bidirectional current).

$$R_{sh} = \frac{V_{sh(max)}}{I_{load(max)}} = \frac{100mV}{10A} = 0.01\Omega$$

$$\pm V_{out(range)} = \pm \frac{V_{REF}}{2} = \pm \frac{5V}{2} = \pm 2.5V$$

$$G_{INA} = \frac{\pm V_{out(range)}}{I_{load(max)} \cdot R_{sh}} = \frac{\pm 2.5V}{10A \cdot 0.01\Omega} = 25V / V$$

2. Calculate the current sense amplifier output range.

$$V_{ina\_outmax} = G_{INA} \cdot (I_{load(max)} \cdot R_{sh}) + \frac{V_{ref}}{2} = (20V / V) \cdot (10A \times 0.01\Omega) + \frac{5V}{2} = 4.5V$$

$$V_{ina\_outmax} = G_{INA} \cdot (I_{load(max)} \cdot R_{sh}) + \frac{V_{ref}}{2} = (20V / V) \cdot (-10A \cdot 0.01\Omega) + \frac{5V}{2} = 0.5V$$

3. Find ADC full-scale input range and results from step 3.

$$ADC_{Full-Scale\ Range} = \pm V_{REF} = \pm 5V$$

4. Find FDA maximum and minimum output for linear operation.

$$0.23V < V_{out} < 4.77V \text{ from THS4551 output low / high specification for linear operation}$$

$$V_{out\_FDA\_max} = 4.77V - 0.23V = 4.54V \text{ Differential max output}$$

$$V_{out\_FDA\_min} = -V_{out\_FDA\_max} = -4.54V \text{ Differential min output}$$

5. Find differential gain based on ADC full-scale input range, FDA output range and results from step 3.

$$Gain = \frac{V_{out\_FDA\_max} - V_{out\_FDA\_min}}{V_{INA\_outmax} - V_{INA\_outmin}} = \frac{4.54V - (-4.54V)}{4.5V - 0.5V} = 2.77V / V$$

$$Gain \approx 2.15V / V \text{ for margin}$$

6. Find standard resistor values for differential gain.

$$Gain_{FDA} = \frac{R_f}{R_g} = 2.15V / V$$

$$\frac{R_f}{R_g} = 2.15V / V = \frac{2.15k\Omega}{1.00k\Omega} = 2.15V / V$$

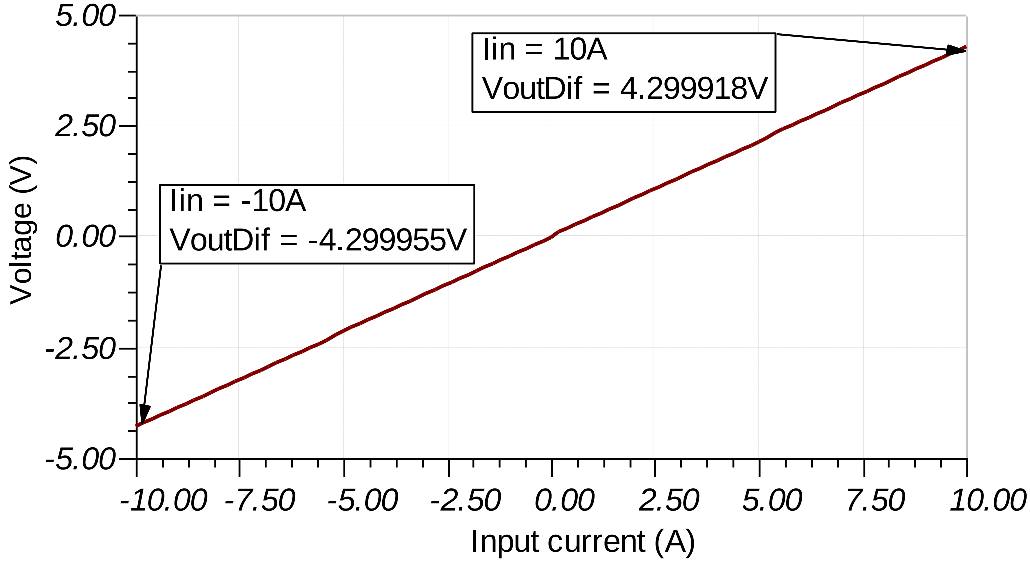
7. Find R_{fINA}, C_{fINA} for cutoff frequency.

$$C_{fINA} = \frac{1}{2 \cdot \pi \cdot f_c \cdot R_{fINA}} = \frac{1}{2 \cdot \pi \cdot 10kHz \cdot 10k\Omega} = 1.591nF \text{ or } 1.5nF \text{ for standard value}$$

$$f_{fina} = \frac{1}{2 \cdot \pi \cdot C_{fINA} \cdot R_f} = \frac{1}{2 \cdot \pi \cdot 1.5nF \cdot 10k\Omega} = 10.6kHz$$

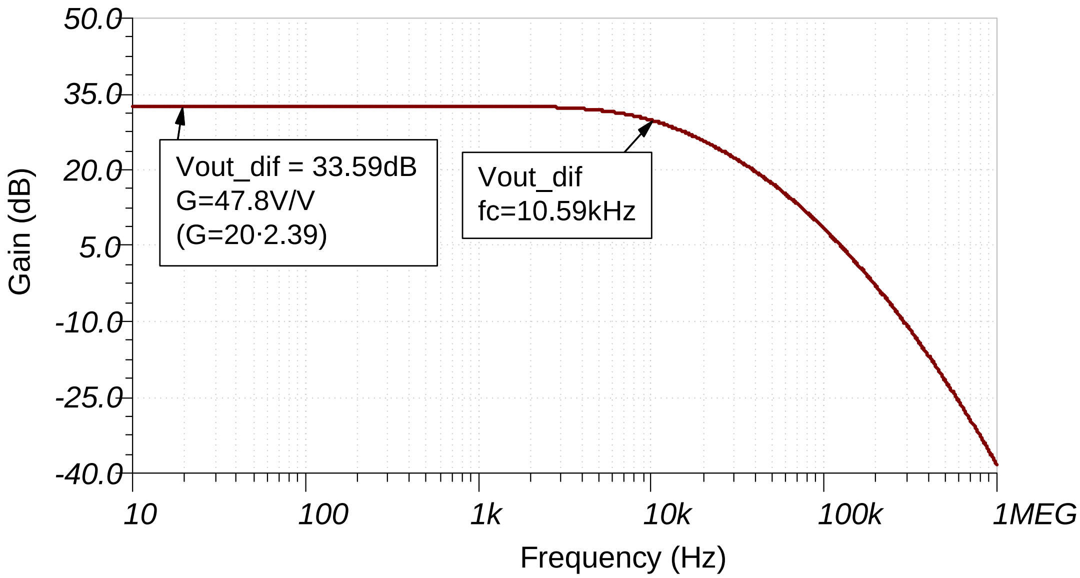
Fully Differential DC Transfer Characteristics

The following graph shows a linear output response for inputs from –10A to +10A.



AC Transfer Characteristics

The bandwidth is simulated to be 10.5kHz and the gain is 32.66dB which is a linear gain of 43V/V (G = 20·2.15V/V).



Noise Simulation

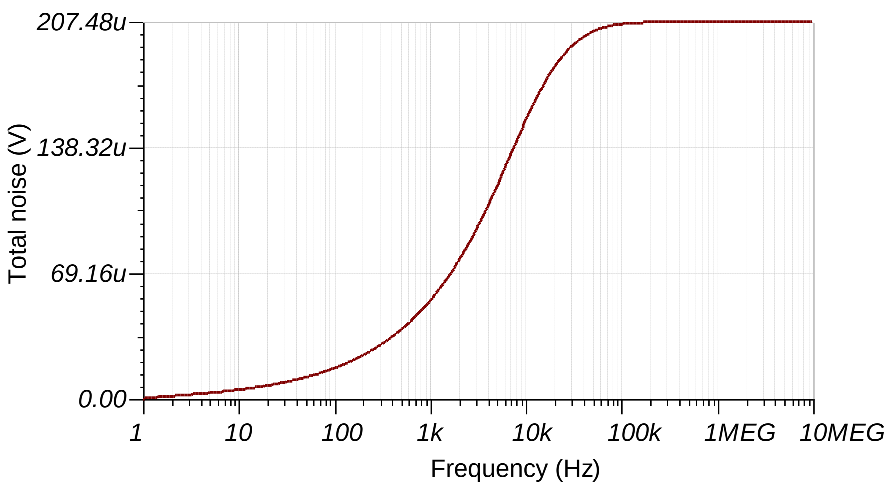
The following simplified noise calculation is provided for a rough estimate. Since the current sense amplifier INA240 is the dominant source of noise, the noise contribution of the OPA320 buffers and THS4521 is omitted in the noise estimate. We neglect resistor noise in this calculation as it is attenuated for frequencies greater than 10.6kHz.

$$f_c = \frac{1}{2\pi \cdot R_{fINA} \cdot C_{fINA}} = \frac{1}{2\pi \cdot 10k\Omega \cdot 1.5nF} = 10.6kHz$$

$$E_{nINA240} = e_{nINA240} \cdot G_{INA} \cdot \sqrt{K_n \cdot f_c} = (40nV / \sqrt{Hz}) \cdot (20V / V) \cdot \sqrt{1.57 \cdot 10.6kHz} = 103.2\mu V$$

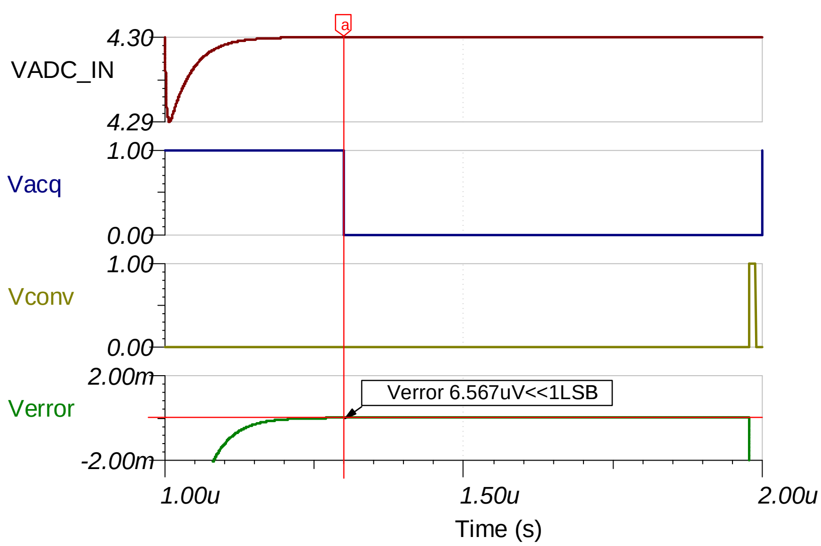
$$E_{nADCIN} = E_{nINA240} \cdot G_{FDA} = (103.2\mu Vrms) \cdot (2.15V / V) = 221.8\mu Vrms$$

Note that calculated and simulated match well. Refer to *Op Amps: Noise 4* for detailed theory on amplifier noise calculations, and *Calculating Total Noise for ADC Systems* for data converter noise.



Transient ADC Input Settling Simulation

The following simulation shows settling to a 10-A DC input signal (ADC differential input signal +4.3V). This type of simulation shows that the sample and hold kickback circuit is properly selected. Refer to *Final SAR ADC Drive Simulations* for detailed theory on this subject.



Design Featured Devices:

Device	Key Features	Link	Similar Devices
ADS8910B[1]	18-bit resolution, 1-Msps sample rate, integrated reference buffer, fully differential input, Vref input range 2.5V to 5V	www.ti.com/product/ADS8910B	www.ti.com/adcs
INA240	High- and low-Side, bi-directional, zero-drift current sense amp, GainError = 0.20%, Gain = 20V/V, wide common-mode = –4V to 80V	www.ti.com/product/INA240	www.ti.com/inas
THS4551	Fully differential amplifier (FDA), 150-MHz bandwidth, Rail-to-Rail output, VosDriftMax = 1.8 µV/°C, e_n = 3.3 nV/rtHz	www.ti.com/product/THS4551	www.ti.com/opamp
OPA320	20-MHz bandwidth, Rail-to-Rail with zero crossover distortion, VosMax = 150 µV, VosDriftMax = 5 µV/C, e_n = 7 nV/rtHz	www.ti.com/product/OPA320	www.ti.com/opamp
REF5050	3 ppm/°C drift, 0.05% initial accuracy, 4 µVpp/V noise	www.ti.com/product/REF5050	www.ti.com/vref

(1) The REF5050 can be directly connected to the ADS8910B without any buffer because the ADS8910B has a built in internal reference buffer. Also, the REF5050 has the required low noise and drift for precision SAR applications. The INA240 offers high common-mode range and low gain error in current sensing solutions. The THS4551 is commonly used in high-speed precision fully differential SAR applications as it has sufficient bandwidth to settle to charge kickback transients from the ADC input sampling. The OPA320 is required to isolate the INA240 from any residual charge kickback at the inputs of the FDA..

Design References

See *Analog Engineer's Circuit Cookbooks* for TI's comprehensive circuit library.

Link to Key Files

ADS8900B Design File – http://www.ti.com/lit/zip/sbam340.