Analog Engineer's Circuit

High-Side Current Shunt Monitor Circuit to 3-V Single-Ended ADC

TEXAS INSTRUMENTS

Art Kay

Input	ADC Input	Digital Output ADS7042
−6A	0.3V	$19A_H$, 410_d
+6A	2.7V	$E66_H$, 3686_d

Power Supplies

AVDD / V_{REF}	DVDD	Vsup
3.0V	1.65V	40V

Design Description

Current shunt monitors are amplifiers that are optimized to read small shunt voltages over very wide common mode ranges. This example application uses the INA190A4 to translate a ±6-A current into a 0-V to 3-V range for the ADC. Note that this is a high sided current measurement with a 40V common mode range. Detailed theory on current sensing is covered in *Using current sense amplifiers to solve today's current sensing design challenges*. Compared to other current shunt devices the INA190 has very low offset voltage, bias current, and drift. This excellent DC performance allows smaller for smaller input voltage ranges without compromising accuracy as the offset is small compared to the input signal. The use of small shunt resistors is an advantage as the power dissipated in the shunt is smaller for smaller resistors for a given current level. The ADS7042 is a 12-bit 1MSPS SAR ADC with a 3V analog input range. The design shown in this document can be modified for other data converters and input ranges. This design can be used a wide range of applications where current needs to be monitored such as notebook computers, cell phones, and battery management.
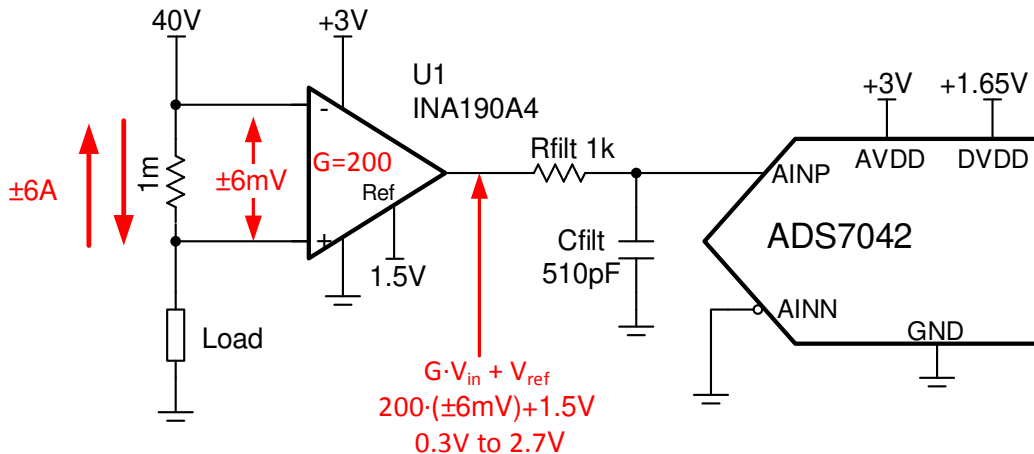
Specifications

Specification	Goal	Calculated	Simulated
Transient Settling	< 0.5LSB = 366µV	NA	0.94µV
Noise	NA	3.5mVrms	3.16mV
Bandwidth	NA	33kHz	35kHz

Design Notes

1. The tolerance in the shunt resistor, R_{SENSE}, will translate into a gain error. Choose the tolerance according to your error budget. Note that the maximum specified gain error for the INA190A4 is 0.3% and a common tolerance 1-m resistor is 0.5% to 1.0%.
2. Selection of the shunt resistor is covered in the component selection section. The objective is to minimize power dissipation while maintaining good accuracy.
3. Use a C0G capacitor for C_{FILT} to minimize distortion.
4. The example design is for a bidirectional current source (for example, ±6A). A similar approach can be followed for an unidirectional current source (for example, 0A to 12A). The main difference is that the reference input pin would connect to ground as opposed to 1/2 V_{REF}.

Component Selection

1. Choose Rsense Resistor and find Gain for the current sense amplifier (bidirectional current)

$$R_{sh} < \frac{P_{max}}{\left(I_{max}\right)^2} = \frac{50mW}{\left(6A\right)^2} = 1.38m\Omega$$

Choose Rsh = 1mΩ

$$\pm V_{out(range)} = \pm \frac{V_{REF}}{2} = \pm \frac{3V}{2} = \pm 1.5V$$

$$G_{INA} = \frac{\pm V_{out(range)}}{I_{load(max)} \cdot R_{sh}} = \frac{\pm 1.5V}{6A \cdot 1m\Omega} = 250V/V$$

Select INA190A4, $G = 200V/V$, Common Mode Range: -0.2 V to 40 V

2. Calculate the current sense amplifier output range

$$V_{INA\_outmax} = G_{INA} \cdot \left(I_{load(max)} \cdot R_{sh}\right) + \frac{V_{REF}}{2} = 200V/V \cdot \left(6A \cdot 1m\Omega\right) + \frac{3V}{2} = 2.7V$$

$$V_{INA\_outmin} = G_{INA} \cdot \left(I_{load(min)} \cdot R_{sh}\right) + \frac{V_{REF}}{2} = 200V/V \cdot \left(-6A \cdot 1m\Omega\right) + \frac{5V}{2} = 0.3V$$

3. Find the INA190 output swing from the data sheet.

Swing to Positive Rail = 3V - 40mV = 2.96V

Swing to Negative Rail = 1mV

The output is scaled for 0.3V to 2.7V, so this design has significant margin.

If desired, a larger shunt resistor could be used to expand the usable range.

4. Offset Error impact on system error.

OutputOffsetINA = $V_{os} \cdot Gain = 15\mu V \cdot 200 = 3mV$

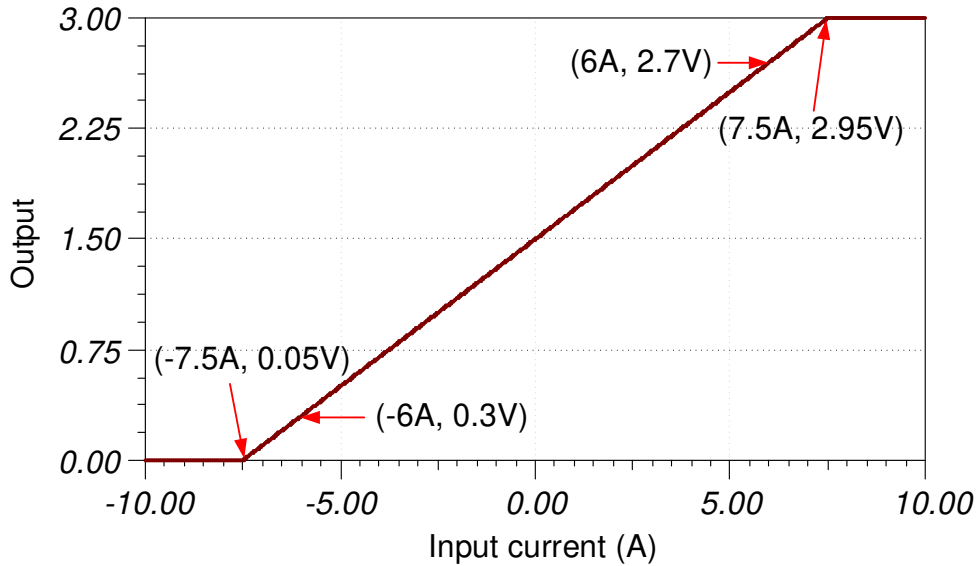OfsetADS7042 = $3LSB \cdot 366\mu V/LSB = 1.1mV$

$$TotalOffsetRSS = \sqrt{\left(3mV\right)^2 + \left(1.1mV\right)^2} = 3.2mV$$

$$Error(\%FSR) = \frac{3.2mV}{3V} \cdot 100 = 0.11\% \text{ of FSR}$$

## DC Transfer Characteristics

The following graph shows a linear output response for inputs from –7.5A to +7.5A. The required linear range is ±6A, so this circuit meets the requirement with design margin.


AC Transfer Characteristics

The data sheet specified bandwidth of 33kHz for the INA190A4 closely matches the simulated 35kHz bandwidth. The input ADC filter is designed to minimize charge kickback and does not limit the bandwidth ($f_{c(ADC\ filter)}$ = 312kHz). See *TI Precision Labs - Op Amps: Bandwidth 1* for more details on this subject.
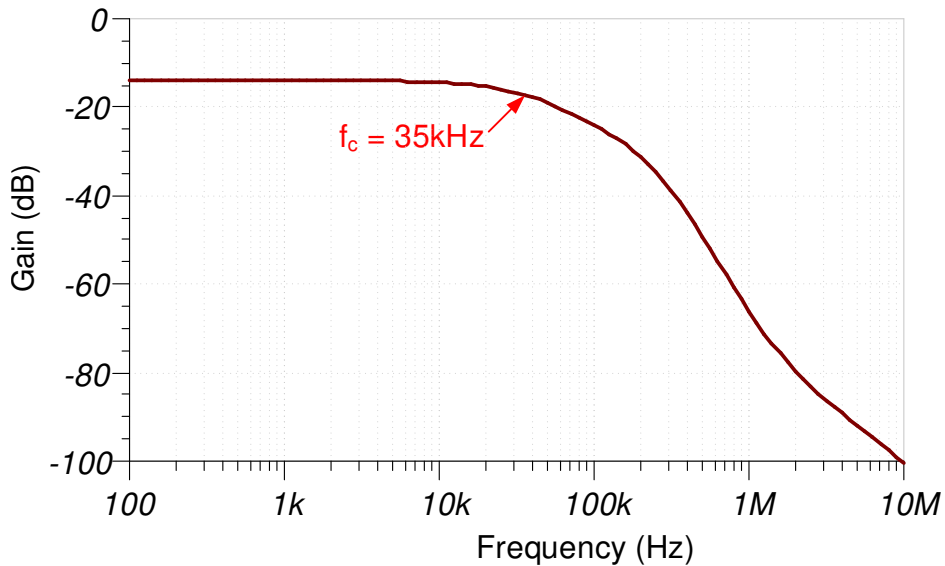
Transient ADC Input Settling Simulation

The transient ADC simulation is performed for a near full scale input (VinADC = 2.3V), for a 100-kHz sampling rate. Note that the sampling rate needed to be adjusted as the INA190 does not have sufficient bandwidth to respond to the transient charge kickback from the ADC at full sampling rate. Refer to *Introduction to SAR ADC Front-End Component Selection* for detailed theory on this subject.
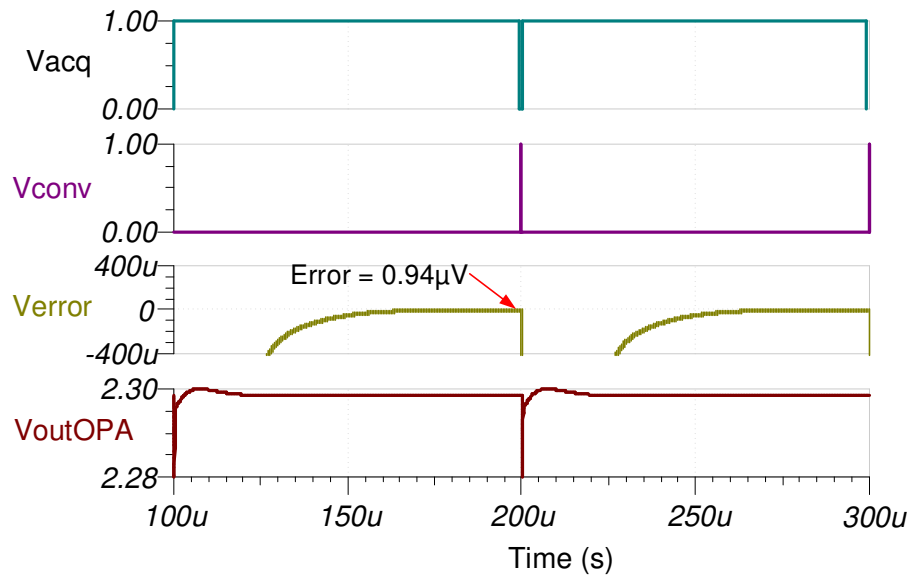
Noise Simulation

The noise hand calculation follows. This calculation assumes that the filter is a first order but inspection of the bandwidth simulation shows a more complex response.

$$E_n = G_n \cdot e_n \cdot \sqrt{K_n \cdot f_c}$$

$$E_n = 200 \cdot 75\,nV\big/\sqrt{Hz} \cdot \sqrt{1.57 \cdot 35kHz} = 3.5mVrms$$

Note that the calculated and simulated match well. Refer to *TI Precision Labs - Op Amps: Noise 4* for detailed theory on amplifier noise calculations, and *Calculating the Total Noise for ADC Systems* for data converter noise.
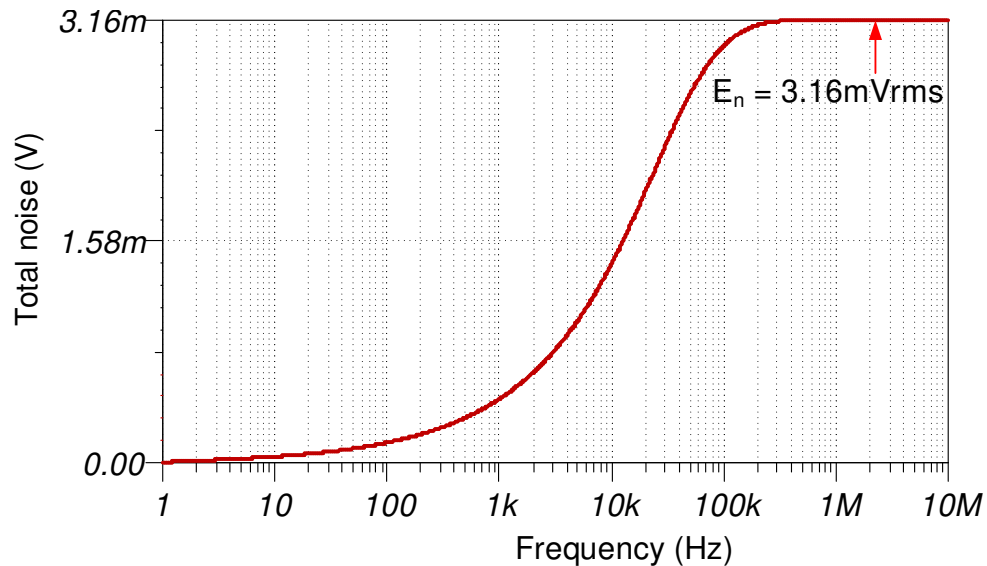
Design Featured Devices

Device	Key Features	Link	Other Possible Devices
ADS7042	12-bit resolution, SPI, 1MSPS sample rate, single-ended input, AVDD/Vref input range 1.6V to 3.6V.	12-Bit 1MSPS Ultra-Low-Power Ultra-Small-Size SAR ADC With SPI Interface	Analog-to-digital converters (ADCs)
INA190	Low Supply voltage (1.7V to 5.5V), Wide Common-Mode (-0.2V to 40V), Low Offset Voltage (Vos < 15µV Max), Low Bias Current (500pA typ).	40-V, Bidirectional, Ultraprecise Current Sense Amplifier with Picoamp IB and ENABLE	Analog current-sense amplifiers

Link to Key Files

Texas Instruments, TINA source files, software support

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