

## Low-side current shunt monitor circuit to 3-V single-ended ADC

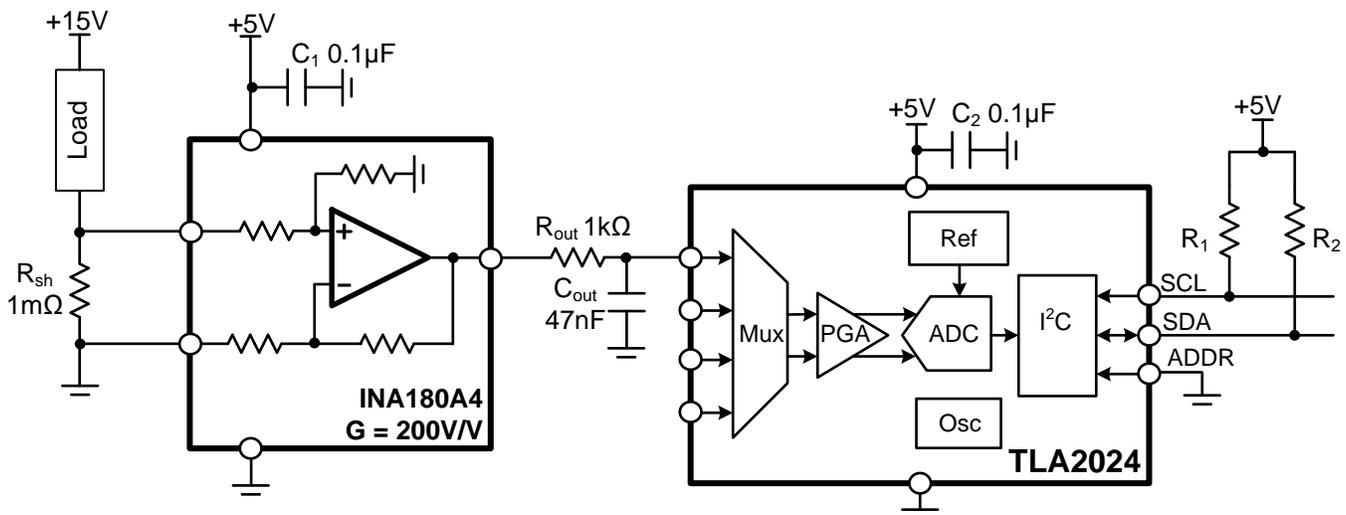
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Input	ADC Input	Digital Output TLA2024
0A	0V	000h
20A	4.0V	7D0h

Power Supplies	
Supply to Monitor	VDD
15V	5V

### Design Description

This design shows how to interface a monolithic current shunt amplifier with a delta-sigma data converter. The [INA180](#) device is a low-cost current shunt amplifier that comes in a wide range of gain values (20, 50, 100, and 200V/V). Although shown as a low-side monitor here, the current shunt amplifier could be used for common-mode voltages to 26V. The [TLA2024](#) device is used as it is a low-cost, 12-bit delta-sigma data converter. This implementation of a current monitor circuit is useful where cost is a concern, but accuracy is still important. Some possible applications are [personal electronics](#), [appliances](#), and [building automation](#).



## Specifications

Specification	Goal	Calculated	Simulated
ADC input range		$\pm 4.096\text{V}$	
ADC resolution		$\pm 4.096\text{V} / 2^{11} = 2\text{mV}$	
Bandwidth	3.3kHz	3.3kHz	3.44kHz
Noise	< 1LSB	$588\mu\text{V}_{\text{RMS}}$ (3.53mVpp)	$572\mu\text{V}_{\text{RMS}}$ (3.43mVpp)
System range	0A to 20A	0.025A to 20A	0A to 20A

## Design Notes

- For lowest distortion, use C0G capacitors for all filters (Cf1, Cf2, Cout).
- The ADC used in this reference design has four channels. The other channels could be used for other monitor activities. If only one channel is required, use the TLA2021 device.
- The input impedance of the delta-sigma device is dependent on the PGA setting. In this reference design, a  $\pm 4.096\text{-V}$  range is used and the corresponding input impedance is  $15\text{M}\Omega$ . The output resistance of the amplifier and the output resistor  $R_{\text{out}}$  form a voltage divider with the ADC input resistance (Error =  $[1 - 15\text{M}\Omega / (15\text{M}\Omega + 1\text{k}\Omega)] \cdot 100 \approx 0.007\%$ ).
- The amplifier used in this design was selected as a low-cost, low-input offset voltage amplifier. In general, cost could further be reduced by selecting an amplifier with a higher offset (TLV9062). Use the *Component Selection* section to confirm that the system errors meet your requirement when selecting different amplifiers. The single-supply, low-side, unidirectional current-sensing circuit covers a similar design.
- When using the multiplexer to cycle through multiple measurements, it is best run the device in singleshot conversion mode. Timing the configuration of the device and the readback of the ADC can be complicated in continuous conversion mode.

### Component Selection

1. Choose the  $R_{\text{sense}}$  resistor and find the gain for the current-sense amplifier.

$$R_{\text{sh}} < \frac{P_{\text{shMax}}}{(I_{\text{shMax}})^2} = \frac{1\text{W}}{(20\text{A})^2} = 1.25\text{m}\Omega \approx 1\text{m}\Omega \text{ (round to common value)}$$

$$V_{\text{shMax}} = I_{\text{shMax}} \cdot R_{\text{shMax}} = (20\text{A}) \cdot (1\text{m}\Omega) = 20\text{mV}$$

$$\text{Gain} = \frac{V_{\text{out(range)}}}{V_{\text{shMax}}} = \frac{4.9\text{V}}{20\text{mV}} = 245\text{V/V} \text{ (round to closest gain for INA180, Gain = 200 for INA180A4)}$$

2. Confirm the minimum and maximum output.

$$V_{\text{INAmax}} = \text{Gain} \cdot (I_{\text{load(max)}} \cdot R_{\text{sh}}) = 200\text{V/V} \cdot (20\text{A} \cdot 1\text{m}\Omega) = 4.0\text{V}$$

$$V_{\text{INAmIn(Ideal)}} = \text{Gain} \cdot (I_{\text{load(min)}} \cdot R_{\text{sh}}) = 200\text{V/V} \cdot (0.0\text{A}) \cdot (1\text{m}\Omega) = 0.0\text{mV}$$

$$V_{\text{INAmIn(limit)}} = 5\text{mV} \text{ from the INA180 Swing to Ground specification}$$

Look at the test condition if the  $A_{\text{ol}}$  specification to find the linear range.

$A_{\text{ol}}$  Test Condition:  $(V^-) + 0.1\text{V} < V_{\text{O}} < (V^+) - 0.1\text{V}$

3. Offset error impact on system error:

$$\text{MaxError} = \frac{V_{\text{os}} \cdot \text{Gain}}{V_{\text{OPAmax}}} \cdot 100 = \frac{100\mu\text{V} \cdot 200}{5.0\text{V}} \cdot 100 = \pm 0.4\%$$

4. This system has a dead zone because of the amplifier output swing limit. The amplifier output will not respond from 0A to  $I_{\text{DeadZone}}$ .

$$I_{\text{DeadZone}} = \frac{\left( \frac{V_{\text{OPAmIn(limit)}}}{\text{Gain}} \right)}{R_{\text{sh}}} = \frac{\left( \frac{5\text{mV}}{200} \right)}{1.0\text{m}\Omega} = 25\text{mA}$$

$$I_{\text{DeadZone}} (\%) = \frac{I_{\text{DeadZone}}}{I_{\text{shMax}}} \cdot 100 = \frac{25\text{mA}}{20\text{A}} \cdot 100 = 0.125\%$$

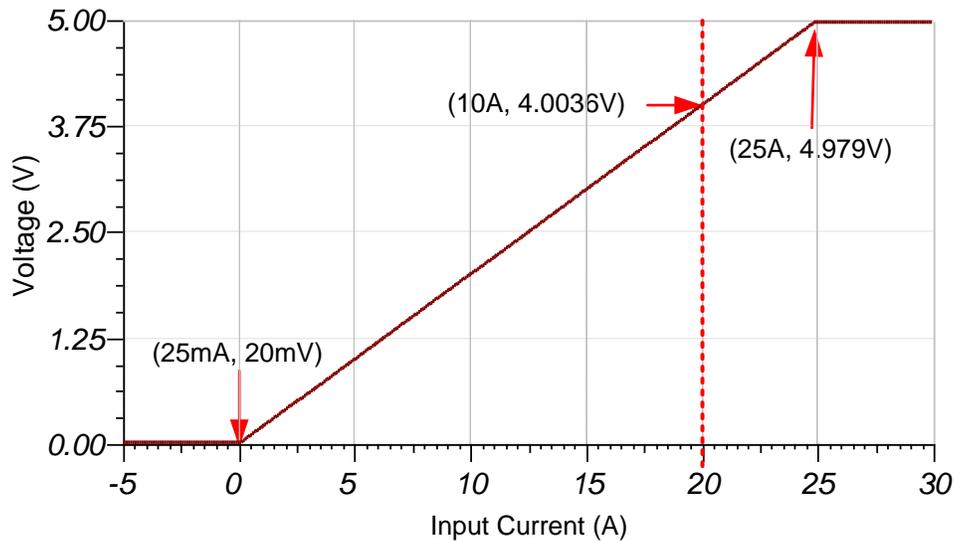
5. Selection of the antialiasing filter capacitor. According to the data sheet, the frequency of the antialiasing filter can be set between the selected data rate and 25kHz. For this design, the filter cutoff is set to the data rate (3.3kHz).

Setting the cutoff at the low end of the range maximizes the attenuation of noise signals.

$$C_{\text{out}} = \frac{1}{2\pi \cdot f_{\text{c}} \cdot R_{\text{out}}} = \frac{1}{2\pi \cdot 3.3\text{kHz} \cdot 1\text{k}\Omega} = 48.2\text{nF} \approx 47\text{nF}$$

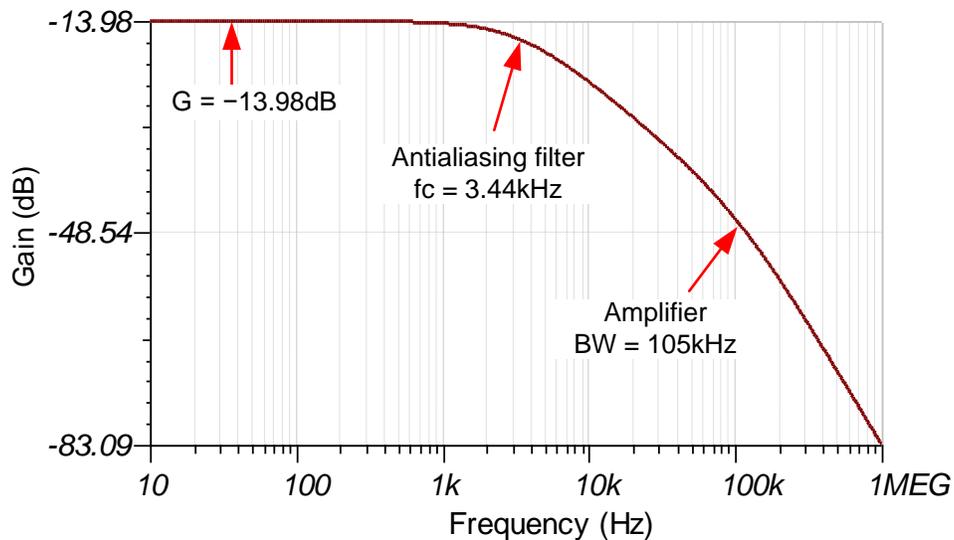
### DC Transfer Characteristics

The following image shows the DC transfer function for the amplifier linear for currents from 0.025A to 20A. The output is not accurate for currents from 0A to 0.025A (0-V to 0.005-V output) because the output swing limitation is violated. The region from 0A to 0.025A is referred to as a dead zone since the output is not accurate in this region.



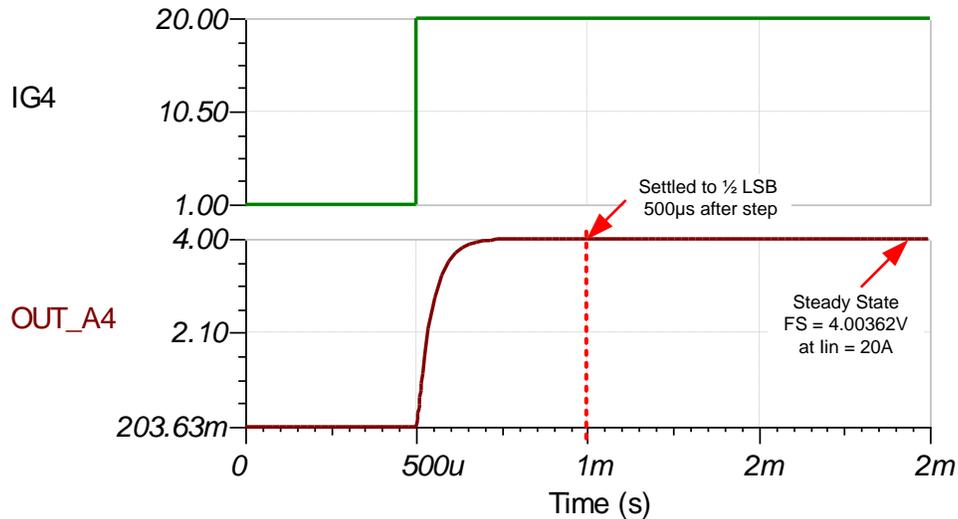
### AC Transfer Characteristics

The bandwidth of the [INA180A4](#) device is 105kHz. Note that the output filter cutoff frequency is set to 3.3kHz, thus the frequency response has two different slopes. The simulated cutoff of 3.44kHz closely matches the theoretical value of 3.3kHz. According to the [TLA202x Cost-Optimized, Ultra-Small, 12-Bit, System-Monitoring ADCs Data Sheet](#), the recommended anti-aliasing filter should be set between the device sampling rate and 25kHz. In this design, the filter was set to 3.3kHz which is the maximum sampling rate of the device.



### Transient ADC Input Settling Simulation

The following image shows the simulated response to a 19-A (1A to 20A, or 1mV to 20mV) step. It takes 380µs for the simulated step to settle to ½ LSB.



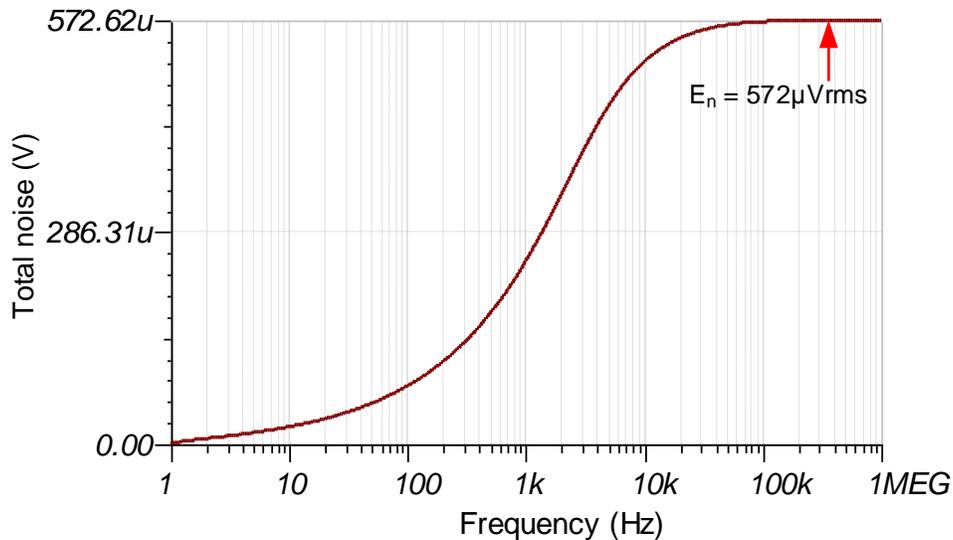
### Noise Simulation

The following simplified noise calculation is provided as a rough estimate of total noise. Also, the bandwidth is estimated at 3.44-kHz first order, but the actual filter is more complex.

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

$$E_n = 200 \cdot 40 \text{ nV} / \sqrt{\text{Hz}} \cdot \sqrt{1.57 \cdot 3.44 \text{ kHz}} = 588 \mu\text{V}_{\text{RMS}}$$

Note that calculated and simulated match well. Refer to the TI Precision Labs - [Op Amps: Noise](#) video series for detailed theory on amplifier noise calculations, and [Calculating the Total Noise for ADC Systems](#) for data converter noise. For an estimate of peak-to-peak noise, multiply by six ( $E_{pp}(\text{simulated}) = 6 \cdot 572 \mu\text{V} = 3.43 \text{ mV}_{pp}$ ). Note that this noise does not include any digital filtering from the ADC.



## Measurement Conversion

Conversions for the shunt measurements are relatively straightforward based on the gain of the shunt resistor voltage and the full-scale range of the ADC. The output voltage of the [TLV333](#) device is calculated from:

### Register Settings

The following table shows how to configure the registers in the [TLA2024](#) device for this example circuit.

Bit	Field	Value	Description
15	OS	1	Start a single conversion
14:12	MUX [2:0]	100	AINP = AIN0, AINN = GND
11:9	PGA [2:0]	001	FSR = $\pm 4.096V$
8	MODE	1	Single-shot conversion mode
7:5	DR [2:0]	111	DR = 3300SPS
4:0	Reserved	00011	Always write 03h

### Pseudocode Example

The following code shows a pseudocode sequence with the required steps to set up the device and the microcontroller that interfaces to the ADC to take subsequent readings from the TLA2024 in singleshot conversion mode. Data is taken by using the maximum data period, allowing for time to wake up the device, configure the ADC, take a single conversion, and set up other ADC measurements. Other measurement channels are similarly used with a write to the configuration register and start of a conversion, wait for the conversion to complete, and a read back of the conversion.

```
Configure microcontroller for I2C communication, I2C address=1001000 (48h)
Loop
{
Send 90h 01h C3h E3h //
// Start write to address 48h, write bit 0 (90h)
// Configuration register 01h
// Set C3E3h, AINO-GND, FSR= $\pm 4.096V$ , Single-shot conversion, DR=3300SPS, stop
Wait 353us // Wait for data period, +10% for internal oscillator variation, +20us
Send 90h 00h 91h xxh xxh // Read back ADC conversion data
// Start write to address 48h, write bit 0 (90h)
// Conversion register 00h, stop
// Start read from address 48h, read bit 1 (91h)
// Read back 2 bytes, stop
}
```

## Design Featured Devices

Device	Key Features	Link	Other Possible Devices
TLA2024	Low-cost, 12-bit, delta-sigma ADC, I2C interface, ultra-small package, integrated reference	<a href="http://www.ti.com/product/TLA2024">http://www.ti.com/product/TLA2024</a>	<a href="http://www.ti.com/adcs">http://www.ti.com/adcs</a>
INA180	Low cost, current-sense amplifier, low-offset 150- $\mu$ V maximum at $V_{cm} = 0V$ , common-mode range $-0.2V$ to $26V$ .	<a href="http://www.ti.com/product/INA180">http://www.ti.com/product/INA180</a>	<a href="http://www.ti.com/currentsense">http://www.ti.com/currentsense</a>

### Link to Key Files

TINA files for Isolated Design - <http://www.ti.com/lit/zip/SBAC246>.

### References

See [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

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