

## Low-side current shunt op-amp circuit to single-ended ADC for cost-optimized monitor

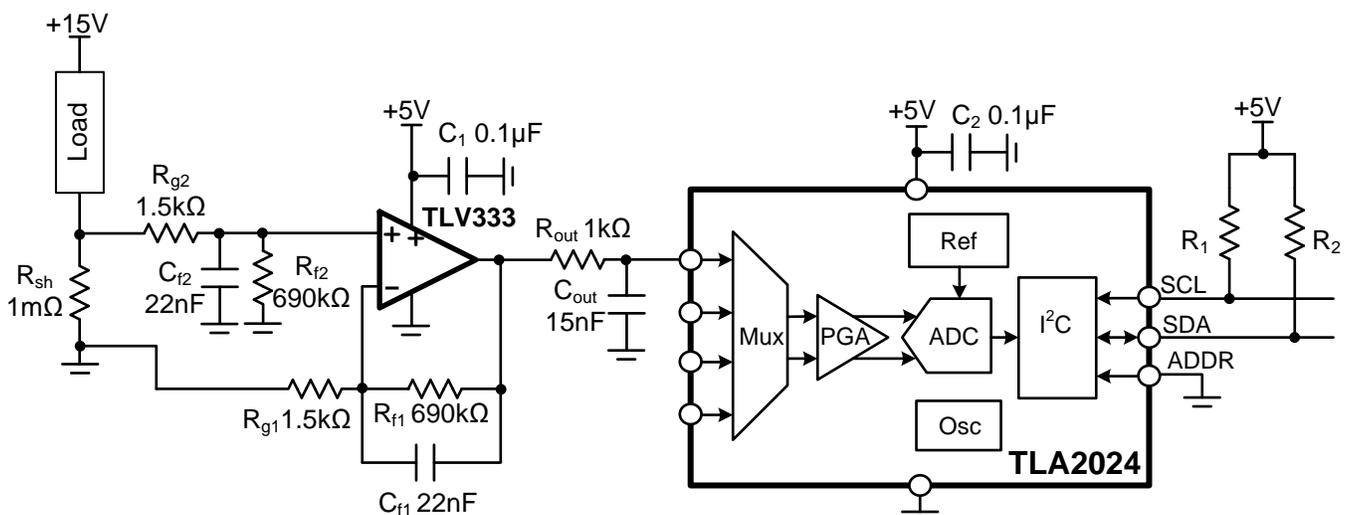
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Input	ADC Input	Digital Output TLA2024
0.217A	0.1V	021 <sub>h</sub> or 33 <sub>d</sub>
10A	4.6V	5FD <sub>h</sub> or 1533 <sub>d</sub>

Power Supplies	
Supply to Monitor	VDD
15V	5V

### Design Description

This design shows a low-side current shunt monitor built using an op amp and a discrete differential-amplifier configuration. This design provides good accuracy at a relatively low cost. The [TLV333](#) op amp is a zero-drift type amplifier so the offset and drift are very low. This allows a low-resistance shunt resistor to be used which minimizes the power dissipated in the shunt resistor and consequently, a physically smaller shunt resistor can be used. The [TLA2024](#) (or [TLA2021](#) for single channel) 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
Input range		$\pm 6.144\text{V}$	
Resolution		$6.144/2^{11} = 3\text{mV}$ (1 LSB)	
Bandwidth	> 100Hz	761Hz	1.1kHz
Noise	< 1 LSB	891 $\mu\text{Vrms}$ (5.35mVpp)	889 $\mu\text{Vrms}$ (5.33mVpp)
Range	0A to 10A	0.2A to 10A	0A to 10A

## Design Notes

- For the lowest distortion use C0G capacitors for all filters ( $C_{f1}$ ,  $C_{f2}$ ,  $C_{out}$ ).
- The ADC used in this reference design has four channels. The other channels may be used for other monitor activities. If only one channel is required, use the TLA2021 device. Note: the TLA2021 device does not have an internal PGA.
- The input impedance of the delta-sigma device is dependent on the PGA setting. In this reference design,  $\pm 6.144\text{-V}$  range is used and the corresponding common-mode input impedance is  $10\text{M}\Omega$  and the differential impedance is  $22\text{M}\Omega$ . The combined input impedance for a single-ended input is the parallel combination of the two ( $10\text{M}\Omega || 22\text{M}\Omega$ ). The output resistance of the amplifier and the output resistor  $R_{out}$  form a voltage divider with the ADC input resistance (Error =  $[1 - 6.88\text{M} / (6.88\text{M} + 1\text{k}\Omega)] \cdot 100 \approx 0.015\%$ ).
- The amplifier used in this design was selected as a low-cost, low-input offset voltage amplifier. In general, cost is further reduced by selecting an amplifier with a higher offset ([TLV9062](#)). Use the *Component Selection* section to confirm that the system errors meet your requirements when selecting different amplifiers. The [Single-supply, low-side, unidirectional current-sensing circuit application report](#) covers a similar design.
- Gain error and gain drift for this circuit is dominated by the external resistors  $R_{f1}$ ,  $R_{f2}$ ,  $R_{g1}$ , and  $R_{g2}$ . For the highest accuracy, use 0.1% and for lower cost use 1%. The [Using SPICE Monte Carlo Tool for Statistical Error Analysis](#) video describes a method for statistically estimating the gain error for the system.
- In this example, the output range of the amplifier was adjusted to 4.6V and the ADC range was adjusted to  $\pm 6.144\text{V}$ . To maximize the ADC range, adjust the amplifier full scale output. For example, the ADC has a  $\pm 4.096\text{-V}$  range, so the full-scale output of the amplifier can be adjusted to match this range.
- When using the multiplexer to cycle through multiple measurements, it is best run the device in single-shot 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 (bidirectional current)

$$R_{\text{sh}} = \frac{P_{\text{shMax}}}{(I_{\text{shMax}})^2} = \frac{100\text{mW}}{(10\text{A})^2} = 1.0\text{m}\Omega$$

$$V_{\text{shMax}} = \frac{P_{\text{shMax}}}{I_{\text{shMax}}} = \frac{100\text{mW}}{10\text{A}} = 10\text{mV}$$

$$G_{\text{opa}} = \frac{V_{\text{out(range)}}}{V_{\text{shMax}}} = \frac{4.6\text{V}}{10\text{mV}} = 460\text{V/V}$$

Select  $R_f = 690\text{k}\Omega$ , and  $R_g = 1.5\text{k}\Omega$  for the inverting gain of  $-460\text{V/V}$  using the [Analog Engineer's Calculator](#) or

$$G_{\text{opa}} = \frac{-R_f}{R_g} = \frac{-690\text{k}\Omega}{1.5\text{k}\Omega} = -460\text{V/V}$$

2. Confirm the minimum and maximum output

$$V_{\text{OPAmax}} = G_{\text{opa}} \cdot (I_{\text{load(max)}} \cdot R_{\text{sh}}) = 460\text{V/V} \cdot (10\text{A} \cdot 1\text{m}\Omega) = 4.6\text{V}$$

$$V_{\text{OPAmin(ideal)}} = G_{\text{opa}} \cdot (I_{\text{load(min)}} \cdot R_{\text{sh}}) = 460\text{V/V} \cdot (0.0\text{A}) \cdot (1\text{m}\Omega) = 0.0\text{mV}$$

$$V_{\text{OPAmin(limit)}} = 100\text{mV} \text{ from the } A_{\text{ol}} \text{ linear range specification for the TLV333 device}$$

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:

$$\text{MaxError} = \frac{V_{\text{os}} \cdot \text{Gain}}{V_{\text{OPAmax}}} \cdot 100 = \frac{15\mu\text{V} \cdot 460}{4.6\text{V}} \cdot 100 = \pm 0.15\%$$

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

See the "optional level-shift" for a method to avoid this limitation.

$$I_{\text{DeadZone}} = \frac{\left( \frac{V_{\text{OPAmin(limit)}}}{G_{\text{opa}}} \right)}{R_{\text{sh}}} = \frac{\left( \frac{0.1\text{V}}{460} \right)}{1.0\text{m}\Omega} = 0.22\text{mA}$$

$$I_{\text{DeadZone}} (\%) = \frac{I_{\text{DeadZone}}}{I_{\text{shMax}}} \cdot 100 = \frac{0.22\text{mA}}{10\text{A}} \cdot 100 = 2.22\%$$

5. Selection of  $R_{\text{in}}$  to limit input current under transient condition. Choose  $I_{\text{in(Max)}} = 10\text{mA}$  from absolute maximum ratings.

$$R_{\text{in}} = \frac{V_{\text{inMax}}}{I_{\text{max}}} = \frac{15\text{V}}{10\text{mA}} = 1.5\text{k}\Omega$$

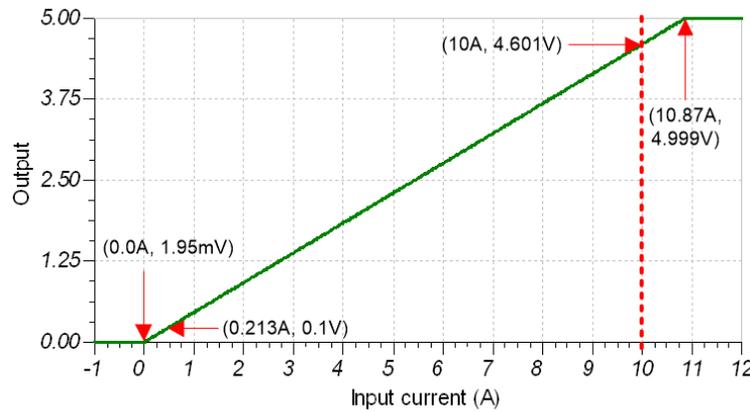
6. Selection of the different capacitors (rounded down to standard value). Note: the amplifier bandwidth is approximately  $761\text{Hz}$  ( $\text{GBP} / G = 350\text{kHz} / 460 = 761\text{Hz}$ ). The bandwidth of the external filters was set to approximately  $10 \times$  the amplifier cutoff.

$$C_f = \frac{1}{2\pi \cdot f_c \cdot R_f} = \frac{1}{2\pi \cdot 10\text{kHz} \cdot 690\text{k}\Omega} = 23.1\text{pF} \approx 22\text{nF}$$

$$C_{\text{out}} = \frac{1}{2\pi \cdot f_c \cdot R_{\text{out}}} = \frac{1}{2\pi \cdot 10\text{kHz} \cdot 1\text{k}\Omega} = 15.9\text{nF} \approx 15\text{nF}$$

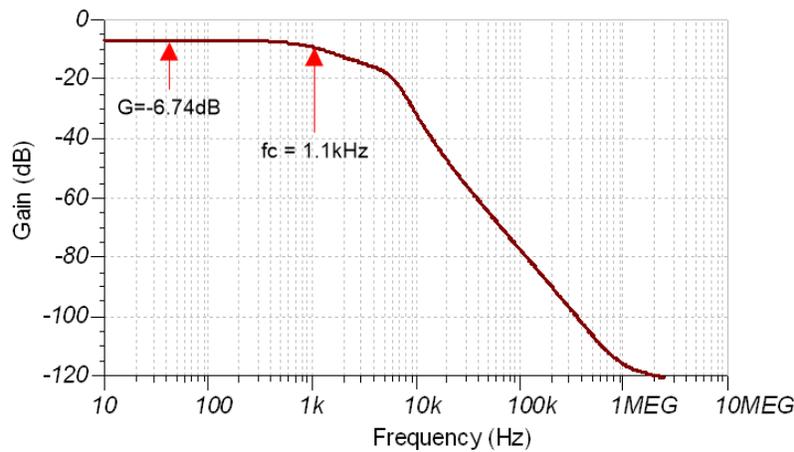
### DC Transfer Characteristics

The DC transfer function for the amplifier linear for currents is from 0.213A to 10A. The output is not accurate for currents from 0A to 0.213A (0-V to 0.1-V output) because the linear output swing limitation is violated. The region from 0A to 0.213A is referred to as a dead zone as the output is not accurate in this region. A circuit modification shown at the end of this document can be used to eliminate the dead zone.



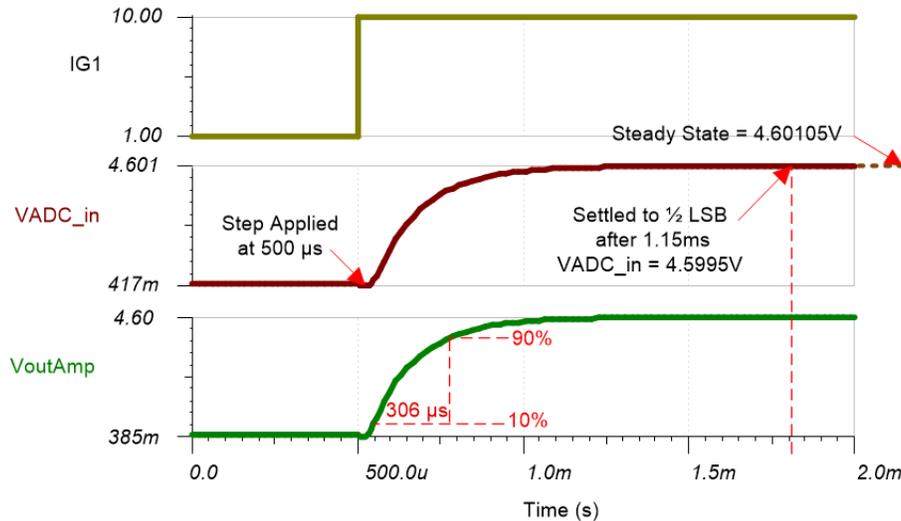
### AC Transfer Characteristics

The gain bandwidth product for the TLV333 device is 350kHz. In a gain of 460, the bandwidth should be approximately  $350\text{kHz} / 460 = 761\text{Hz}$ . Simulated results show a bandwidth of about 1.1kHz. Note that the external filters are all set to a frequency of about 10kHz, this is why the frequency response has two different slopes. The bandwidth of this circuit can be adjusted by selecting a wider bandwidth amplifier and adjusting the external filters. Be careful; however, when selecting an amplifier to look at offset voltage, common-mode range, and swing as the *Component Selection* section of this document shows. See the TI Precision Labs - [Op Amps: Bandwidth](#) video series for more details.



### Transient ADC Input Settling Simulation

The simulated response to a 9-A (1A to 10A, or 1mV to 9mV) step is shown. It takes 1.15ms for the simulated step to settle to ½ LSB. The input step voltage is 9mV, so the step response is a small signal step and is limited by bandwidth (rise time  $t_r = 0.35 / f_c = 0.35 / 1.1\text{kHz} = 318\mu\text{s}$ ).



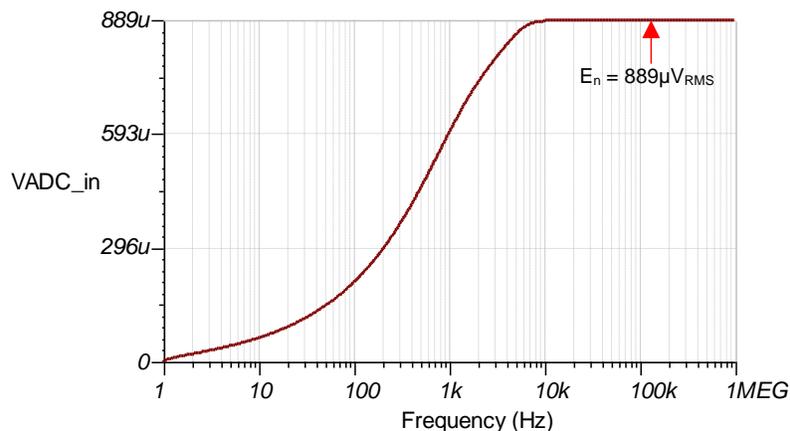
### Noise Simulation

The following simplified noise calculation is provided as a rough estimate of total noise. The resistor noise is neglected as the amplifier noise is high compared to the resistor noise ( $55\text{nV} / \sqrt{\text{Hz}}$  vs about  $4\text{nV} / \sqrt{\text{Hz}}$  from 1-k $\Omega$  resistors). Also, the bandwidth is estimated at 1.1kHz 3rd order, but the actual filter is more complex.

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

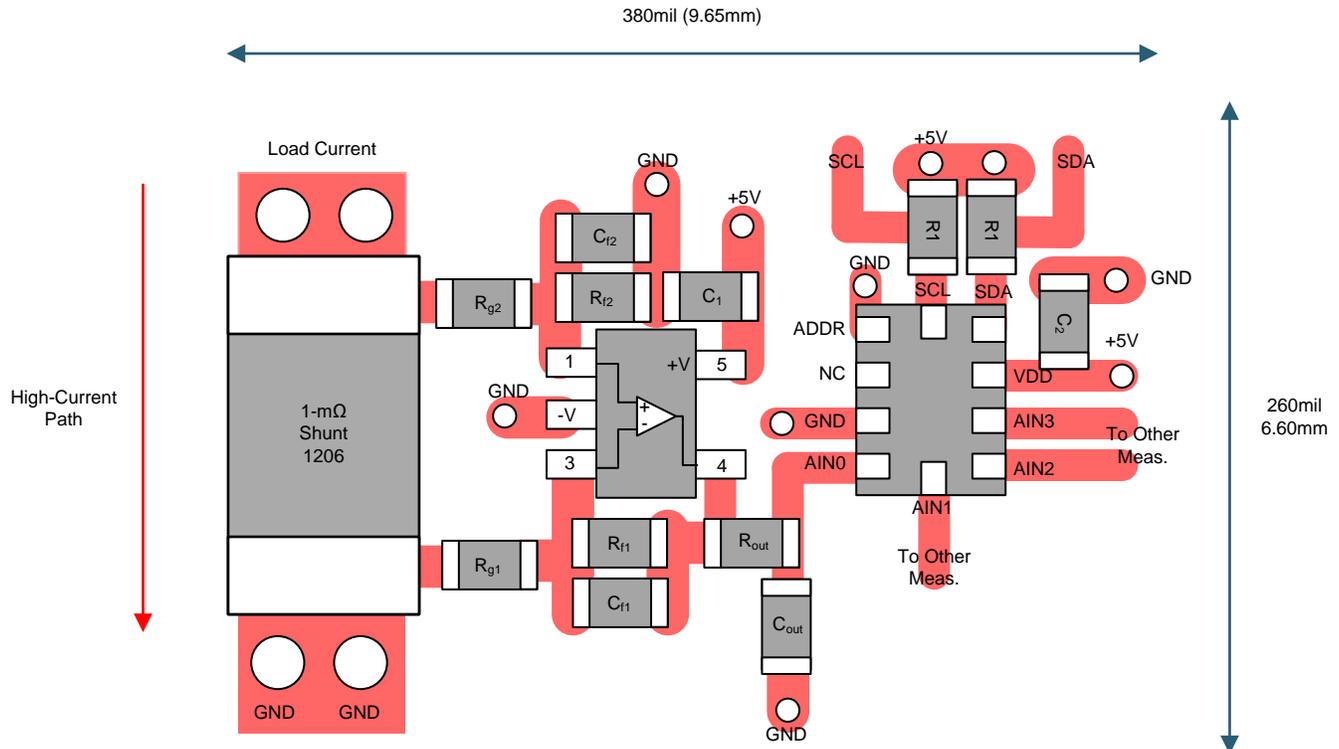
$$E_n = 460 \cdot 55\text{nV} / \sqrt{\text{Hz}} \cdot \sqrt{1.13 \cdot 1.1\text{kHz}} = 891\mu\text{V}_{\text{RMS}}$$

Note that calculated and simulated match well. See 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 ( $E_{pp}(\text{simulated}) = 6 \cdot 891\mu\text{V} = 5.35\text{mV}_{\text{pp}}$ ). Note that the peak-to-peak noise is approximately the size of 1 LSB (1 LSB = 3mV).



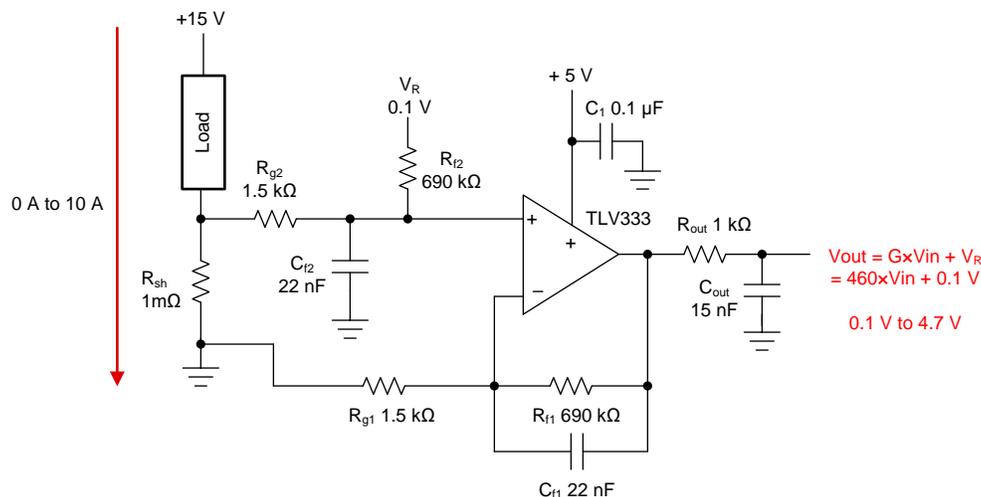
## PCB Layout

The PCB layout gives a general sense of the size of the layout. A 1206 resistor footprint was used for the 0.25-W, 1-m $\Omega$  shunt. Notice that the voltage across the shunt is measured directly at the ends of the resistor. This is called a Kelvin connection and eliminates errors from parasitic resistance in the current path.



## Optional Level Shift

As previously mentioned, the amplifier output swing is limited for output voltages from 0V to 0.1V. One way to eliminate this problem is to shift the output so that the output is 0.1V when 0A is flowing. For a differential-amp configuration, the offset shift can be accomplished by connecting Rf2 to a reference voltage. In this example, a 0.1-V reference voltage is used to provide a linear output from 0.1V to 4.7V for a 0A to 10A input. A larger reference voltage, such as 2.5V, could be used to read bidirectional current (–5A to +5A gives 0.2V to 4.8V out with a 2.5-V reference).



## 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 with the following:

$$V_{AIN0} = I_{shunt} \cdot R_{shunt} \cdot Gain = I_{shunt} \cdot (1m\Omega) \cdot (460 V / V)$$

At the same time, the ADC measurement is converted to the output voltage:

$$OutputCode = \frac{2^{11} \cdot V_{AIN0}}{V_{range}} = \frac{2^{11} \cdot V_{AIN0}}{6.144 V}$$

$$V_{AIN0} = \frac{OutputCode \cdot 6.144 V}{2^{11}}$$

Converting the output code to the shunt current:

$$I_{shunt} = \frac{OutputCode \cdot 6.144 V}{2^{11} \cdot 1m\Omega \cdot 460} = (6.52174 mA) \cdot OutputCode$$

## Register Settings

The following table shows how to configure the registers in the [TLA2024](#) 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]	000	FSR = ±6.144V
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 example 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 single-shot 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 C1h E3h //
// Start write to address 48h, write bit 0 (90h)
// Configuration register 01h
// Set C1E3h, AIN0-GND, FSR=±6.144V, 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>
TLV333	Low cost for excellent offset and drift performance, offset 15 $\mu$ V (max), small package	<a href="http://www.ti.com/product/TLV333">http://www.ti.com/product/TLV333</a>	<a href="http://www.ti.com/opamps">http://www.ti.com/opamps</a>

### Link to Key Files

Source files for this circuit - <http://www.ti.com/lit/zip/SBAC245>.

### References

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

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