**High-voltage battery monitor circuit: ±20V, 0–10kHz, 18-bit fully differential**

Bryan McKay, Arthur Kay

<table>
<thead>
<tr>
<th>Input</th>
<th>ADC Input</th>
<th>Digital Output ADS8910</th>
</tr>
</thead>
<tbody>
<tr>
<td>VinMin = –20V</td>
<td>VoutDif = 4.8V, VoutP = 4.9V, VoutN = 0.1V</td>
<td>1EB85 H or 125829 10</td>
</tr>
<tr>
<td>VinMax = 20V</td>
<td>VoutDif = –4.8V, VoutP = 0.1V, VoutN = 4.9V</td>
<td>2147B H or –125829 10</td>
</tr>
</tbody>
</table>

**Power Supplies**

<table>
<thead>
<tr>
<th>Vcc</th>
<th>Vee</th>
<th>Vref</th>
<th>Vcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3 V</td>
<td>0 V</td>
<td>5 V</td>
<td>2.5 V</td>
</tr>
</tbody>
</table>

**Design Description**

This design translates an input bipolar signal of ±20V into a fully differential ADC differential input scale of ±4.8V, which is within the output linear operation of amplifiers. The values in the *component selection* section can be adjusted to allow for different input voltage 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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Calculated</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient ADC Input Settling</td>
<td>&lt; 0.5 LSB or 19 µV</td>
<td>6.6 µV</td>
<td>N/A</td>
</tr>
<tr>
<td>Noise</td>
<td>20.7 µV rms</td>
<td>20.65 µV rms</td>
<td>30.8 µV rms</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10.2 kHz</td>
<td>10.4 kHz</td>
<td>10.4 kHz</td>
</tr>
</tbody>
</table>

Design Notes

1. Determine the linear range of the op amp based on common mode, output swing, and linear open-loop gain specification. This is covered in the component selection section.

2. For capacitors in the signal path, select COG type to minimize distortion. In this circuit Cf1, Cf2, Cf3, Cf4, Cfilt1, and Cfilt2 need to be COG type.

3. Use 0.1% 20 ppm/°C film resistors or better for good gain drift and to minimize distortion.


5. 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

1. The general equation for this circuit.
   \[ V_{\text{outMinOpa}} = \frac{V_{\text{outMin}} + V_{\text{cm}}}{2} \]
   \[ V_{\text{outMaxOpa}} = \frac{V_{\text{outMax}} + V_{\text{cm}}}{2} \]
   \[ V_{\text{outDiff}} = V_{\text{inDiff}} \times \text{Gain}_\text{diff} \]
   \[ \text{Gain}_\text{diff} = 2 \times \frac{R_f}{R_g} \]

2. Find op amp maximum and minimum output for linear operation.
   \[-0.1 V < V_{\text{cm}} < 5.1 V \quad \text{from OPA320 Vcm specification} \]
   \[0.035 V < V_{\text{out}} < 4.965 V \quad \text{from OPA320 Vout swing specification} \]
   \[0.1 V < V_{\text{out}} < 4.9 V \quad \text{from OPA320 Aol specification for linear operation} \]
   \[0.1 V < V_{\text{out}} < 4.9 V \quad \text{Combined worst case} \]

3. Rearrange the equation from part 1 and solve for VoutDiffMin and VoutDiffMax. Find maximum and minimum differential output voltage based on combined worst case from step 2.
   \[ V_{\text{outDiffMax}} = 2 \cdot V_{\text{outMaxOpa}} - 2 \cdot V_{\text{cm}} = 2 \cdot (4.9 V) - 2 \cdot (2.5 V) = 4.8 V \]
   \[ V_{\text{outDiffMin}} = 2 \cdot V_{\text{outMinOpa}} - 2 \cdot V_{\text{cm}} = 2 \cdot (0.1 V) - 2 \cdot (2.5 V) = -4.8 V \]

4. Find differential gain based on results from step 3.
   \[ \text{Gain} = \frac{V_{\text{outDiffMax}} - V_{\text{outDiffMin}}}{V_{\text{inDiffMax}} - V_{\text{inDiffMin}}} = \frac{(4.8 V) - (-4.8 V)}{(20 V) - (-20 V)} = 0.24 \]

5. Find standard resistor values for differential gain. Use Analog Engineer’s Calculator (“Amplifier and Comparator: Find Amplifier Gain” section) to find standard values for Rf/Rg ratio.
   \[ \frac{\text{Gain}_{\text{diff}}}{2} = \frac{R_f}{R_g} = \frac{0.24}{2} = 0.12 \]
   \[ \frac{R_f}{R_g} = 0.12 = \frac{12 \, \Omega}{100 \, \Omega} = 0.12 \]

6. Find Cf for cutoff frequency.
   \[ f = \frac{1}{2 \cdot \pi \cdot C_f \cdot R_f} = \frac{1}{2 \cdot \pi \cdot (1.3 \, \text{nF}) \cdot (12 \, \Omega)} = 10.2 \, \text{kHz} \]
   \[ C_f = \frac{1}{2 \cdot \pi \cdot f \cdot R_f} = \frac{1}{2 \cdot \pi \cdot (10 \, \text{kHz}) \cdot (12 \, \Omega)} = 1.326 \, \text{nF} \quad \text{or 1.3 nF for standard value} \]
   \[ f = \frac{1}{2 \cdot \pi \cdot C_f \cdot R_f} = \frac{1}{2 \cdot \pi \cdot (1.3 \, \text{nF}) \cdot (12 \, \Omega)} = 10.2 \, \text{kHz} \]
**DC Transfer Characteristics**

The following graph shows a linear output response for inputs from –20V to +20V. Refer to *Determining a SAR ADC’s Linear Range when using Operational Amplifiers* for detailed theory on this subject.

![DC Transfer Characteristics Graph](image)

**AC Transfer Characteristics**

The bandwidth is simulated to be 10.4 kHz, and the gain is –12.4dB which is a linear gain of 0.12. See *Op Amps: Bandwidth 1* for more details on this subject.

![AC Transfer Characteristics Graph](image)
Transient ADC Input Settling Simulation

The following simulation shows settling to a –20V dc input signal. This type of simulation shows that the sample and hold kickback circuit is properly selected. Refer to *Introduction to SAR ADC Front-End Component Selection* for detailed theory on this subject.

**Noise Simulation**

The following simplified noise calculation is provided for a rough estimate. We neglect resistor noise in this calculation as it is attenuated for frequencies greater than 10kHz.

\[
\begin{align*}
    f_c &= \frac{1}{2 \pi R_{m2} C_{m2}} = \frac{1}{2 \pi (47.5\,\text{k}\Omega) (1.2\,\text{nF})} = 2.8\,\text{MHz} \\
    E_{n,se} &= 2 \times \frac{7\,\text{nV}}{\sqrt{1 + (1.57 \times 2.8\,\text{MHz})}} = 7.1\,\text{mVrms} \quad \text{for a single ended input} \\
    E_{n,tot} &= \sqrt{E_{n,se}^2 + E_{n,se}^2} = \sqrt{(14.7\,\text{mV})^2 + (14.7\,\text{mV})^2} = 20.7\,\text{mV rms} \quad \text{Total noise for differential amplifier}
\end{align*}
\]

Note that calculated and simulated match well. Refer to *Calculating the Total Noise for ADC Systems* for detailed theory on this subject.
Measure FFT

This performance was measured on a modified version of the ADS8910BEVM. The AC performance indicates SNR = 99.4dB, and THD = –116.4dB. See *Introduction to Frequency Domain* for more details on this subject.

Noise Measurement

The following measured result is for both inputs connected to ground. The histogram shows the system offset and noise. The standard deviation in codes is given by the EVM GUI (0.81), and this can be used to calculate the RMS noise (30.9µV rms) as shown in the following equation.

\[
\text{LSB} = \frac{\text{FSR}}{2^N} = \frac{10 \text{ V}}{2^{18}} = 38.14 \mu\text{V}
\]

\[
E_{n,\text{measured}} = E_{n,\text{Sigma}} \cdot \text{LSB} = (0.81) \cdot (34.14 \mu\text{V}) = 30.9 \mu\text{Vrms}
\]
Design Featured Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Key Features</th>
<th>Link</th>
<th>Similar Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>differential input, Vref input range 2.5V to 5V.</td>
<td><a href="http://www.ti.com/adcs">www.ti.com/adcs</a></td>
<td></td>
</tr>
<tr>
<td></td>
<td>µV, VosDriftMax = 5uV/°C, en = 7nV/rtHz</td>
<td><a href="#">2</a></td>
<td></td>
</tr>
<tr>
<td>REF5050[3]</td>
<td>3 ppm/°C drift, 0.05% initial accuracy, 4µVpp/V noise</td>
<td><a href="#">3</a></td>
<td><a href="http://www.ti.com/vref">www.ti.com/vref</a></td>
</tr>
</tbody>
</table>

(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 ADC applications. The OPA320 is also commonly used in 1Msps SAR applications as it has sufficient bandwidth to settle to charge kickback transients from the ADC input sampling. Furthermore, the zero crossover distortion rail-to-rail input allows for linear swing across most of the ADC input range.

(2) 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 ADC applications. The OPA320 is also commonly used in 1Msps SAR applications as it has sufficient bandwidth.

(3) 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 ADC applications. The OPA320 is also commonly used in 1Msps SAR applications as it has sufficient bandwidth.

Link to Key Files for High Voltage Battery Monitor

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


Revision History

<table>
<thead>
<tr>
<th>Revision</th>
<th>Date</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>January 2019</td>
<td>Downstyle title, update title role content, added link to circuit cookbook library page.</td>
</tr>
</tbody>
</table>
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