Analog Engineer's Circuit

Circuit for Driving a Switched-Capacitor SAR ADC With a Buffered Instrumentation Amplifier

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Input	ADC Input	Digital Output ADS8860
–10mV	Out = 0.2V	$0A3D_H$ or 2621_{10}
5mV	Out = 4.8V	$F5C3_H$ or 62915_{10}

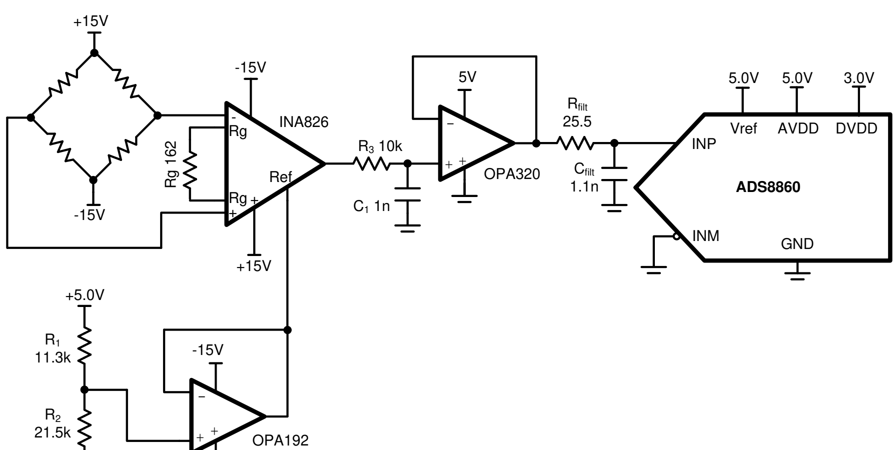
Power Supplies

AVDD	DVDD	V_{ref_INA}	V_{ref}	V_{cc}	V_{ee}
5.0V	3V	3.277V	5.0V	15V	–15V

Design Description

Instrumentation amplifiers are a common way of translating low-level sensor outputs to high-level signals to drive an ADC. Typically, instrumentation amplifiers are optimized for low noise, low offset, and low drift. Unfortunately, the bandwidth of many instrumentation amplifiers may not be sufficient to achieve good settling to ADC charge kickback at maximum sampling rates. This document shows how a wide-bandwidth buffer can be used with an instrumentation amplifier to achieve good settling at high sampling rates. Furthermore, many instrumentation amplifiers are optimized for high voltage supplies and it can be required to interface the high voltage output (that is, ±15V) to a lower voltage amplifier (for example, 5V). This design shows how a current-limiting resistor can protect the amplifier from electrical overstress in cases where the instrumentation amplifier is outside the input range of the op amp. A related cookbook circuit shows a simplified approach that does not include the wide-bandwidth buffer (*Driving a Switched-Capacitor SAR With an Instrumentation Amplifier* circuit design). The simplified approach has limited sampling rate as compared to the buffered design. Note that the following circuit shows a bridge sensor, but this method could be used for a wide range of different sensors.

This circuit implementation is applicable in applications such as *analog input modules*, *electrocardiograms (ECGs)*, *pulse oximeters*, *lab instrumentation*, and *control units for rail transport*.



Specifications

Specification	Calculated	Simulated
Sampling rate	1Msps	1Msps, settling to –44µV
Offset (ADC Input)	40µV × 306.7 = 12.27mV	16mV
Offset Drift	(0.4µV/°C) × 306.7 = 123µV/°C	N/A
Noise	978µV	586µV_{RMS}

Design Notes

1. The bandwidth of instrumentation amplifiers is typically too low to drive SAR data converters at high data rates (the INA826 bandwidth is 10.4kHz for a gain of 305V/V in this example). Wide bandwidth is needed because the SAR has a switched capacitor input that needs to be charged during each conversion cycle. The OPA320 buffer was added to allow the ADC to run at full data rate (ADS8860 1Msps).
2. Select the gain to achieve an input swing that matches the input range of the ADC. Use the instrumentation amplifier reference pin to shift the signal offset to match the input range. This is covered in the *component selection* section.
3. The INA826 gain is scaled so that the op amp input voltage levels are inside the normal operating range of the amplifier. However, during power up or when a sensor is disconnected the output can drive to either power supply rail (±15V). The resistor R_3 is used to limit the current . This is covered in the *Overvoltage Protection Filter Between Instrumentation Amplifier and Op Amp* section of this document.
4. The buffer amplifier following the voltage divider is required for driving the reference input of most instrumentation amplifiers. Choose precision resistors and a precision low offset amplifier as the buffer. Refer to *Selecting the right op amp* for more details on this subject.
5. Check the common mode range of the amplifier using the *Common-Mode Input Range Calculator for Instrumentation Amplifiers* software tool.
6. Select COG capacitors for C_1, and C_{filt} to minimize distortion.
7. Use 0.1% 20ppm/°C film resistors or better for the gain set resistor R_g. The error and drift of this resistor directly translates into gain error and gain drift.
8. The *Precision labs series: Analog-to-digital converters (ADCs)* training video series methods for selecting the charge bucket circuit R_{filt} and C_{filt}. Refer to the *Introduction to SAR ADC Front-End Component Selection* for details on this subject.

Component Selection

1. Find the gain set resistor for the instrumentation amplifier to set the output swing to 0.2V to 4.8V.

$$Gain = \frac{V_{out\_max} - V_{out\_min}}{V_{in\_max} - V_{in\_min}} = \frac{4.9V - 0.2V}{5mV - (-10mV)} = 306.7$$

$$Gain = 1 + \frac{49.4k\Omega}{R_g}$$

$$R_g = \frac{49.4k\Omega}{Gain - 1.0} = \frac{49.4k\Omega}{(306.7) - 1.0} = 151.6\Omega \text{ or } 162\Omega \text{ for standard } 0.1\% \text{ resistor}$$

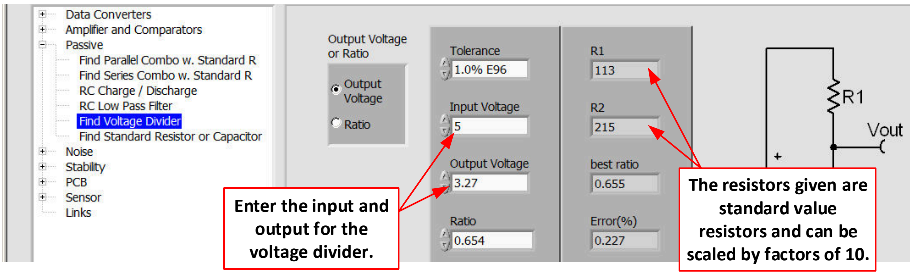
2. Find the INA826 reference voltage (Vref) to shift the output swing to the proper voltage level.

$$V_{out} = Gain \cdot V_{in} + V_{ref\_INA}$$

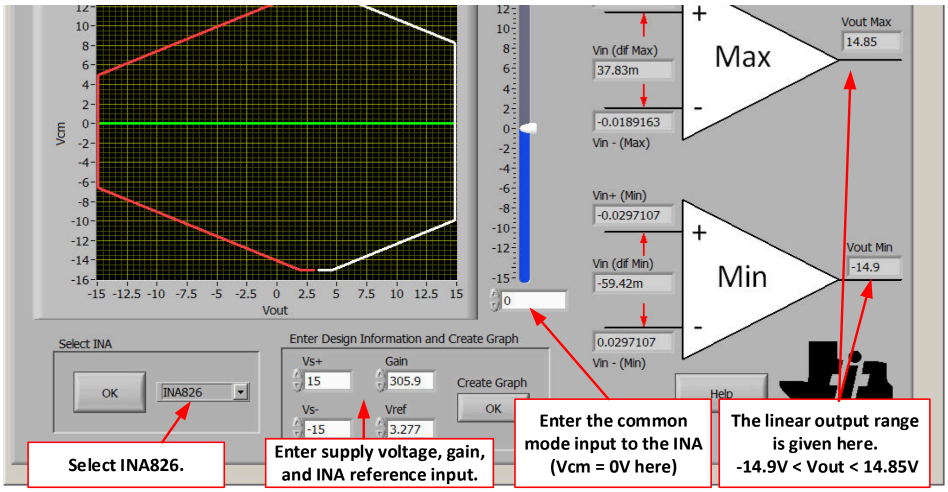
$$V_{ref\_INA} = V_{out} - Gain \cdot V_{in} = 4.8V - \left(1 + \frac{49.4k\Omega}{162\Omega}\right) \cdot (5mV) = 3.27V$$

3. Select standard value resistors to set the INA826 reference voltage (V_{ref_INA} = 3.27V). Use the *Analog Engineer's Calculator* ("Passive\Find Voltage Divider" section) to find standard values for the voltage divider.

$$V_{ref\_INA} = \frac{R_2}{R_1 + R_2} \cdot V_{in\_div} = \frac{21.5k\Omega}{11.3k\Omega + 21.5k\Omega} \cdot (5V) = 3.277V$$

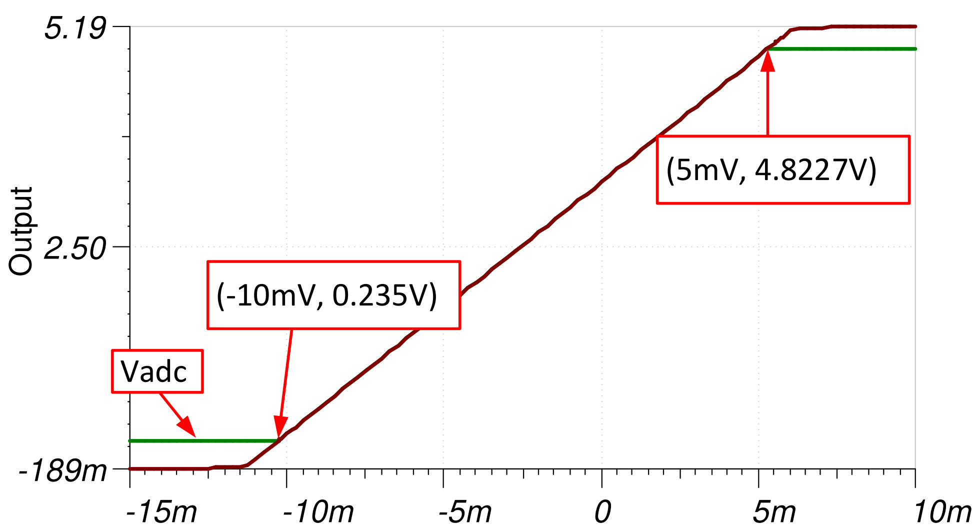


4. Use the *Common-Mode Input Range Calculator for Instrumentation Amplifiers* to determine if the INA826 is violating the common mode range.



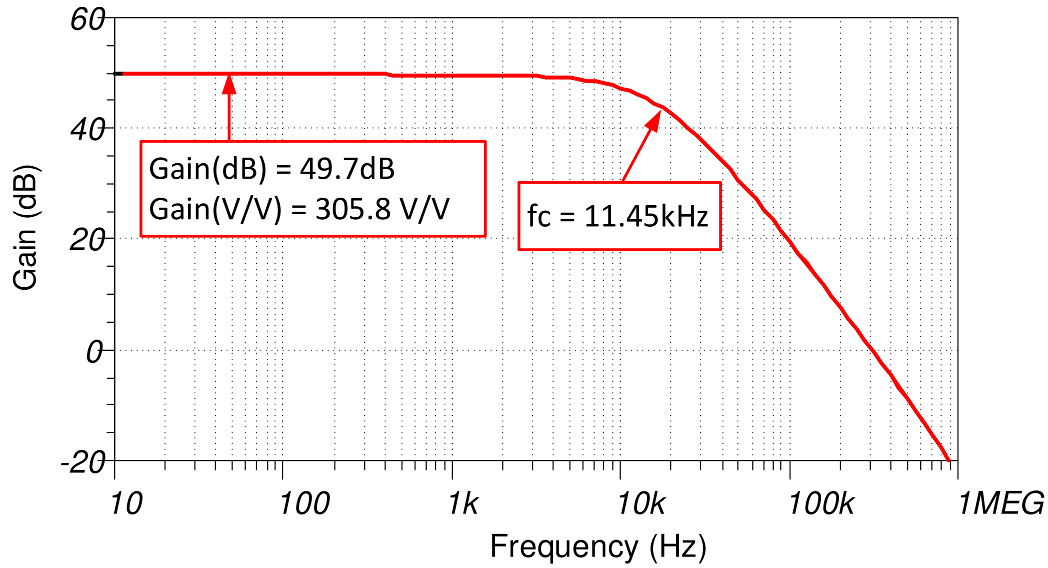
DC Transfer Characteristics

The following graph shows a linear output response for inputs from –5mV to +15mV. Refer to *Determining a SAR ADC's Linear Range when using Instrumentation Amplifiers* for detailed theory on this subject. In cases where the INA826 output exceeds the op amp input range, the ESD diodes turn on and limit the input. The resistor R3 protects the amplifier from damage by limiting the input current (see the *Overvoltage Protection Filter Between Instrumentation Amplifier and Op Amp* section). The op amp output is inside the absolute maximum rating of the ADS8860 (–0.3V < V_{IN} < REF +0.3V).



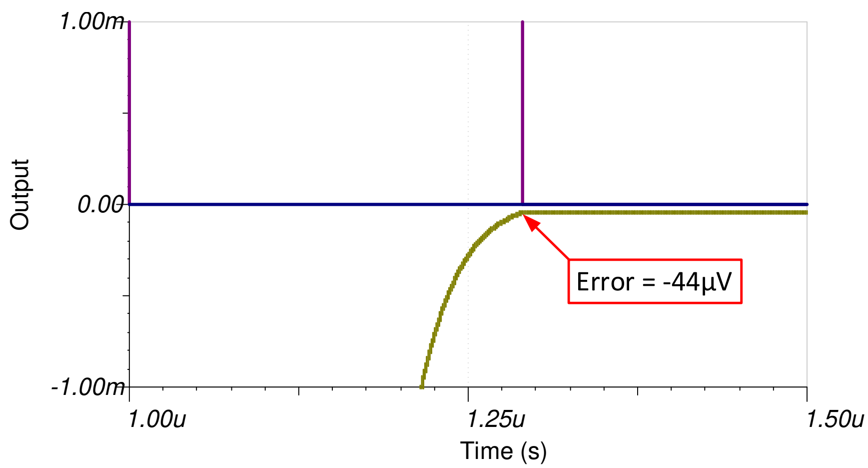
AC Transfer Characteristics

The bandwidth is simulated to be 11.45 kHz in this configuration. In this bandwidth it is not possible to drive the SAR converter at full speed. See the *TI Precision Labs* video series *Op Amps: Bandwidth 1* for more details on this subject.



Transient ADC Input Settling Simulation

The OPA320 buffer (20MHz) is used because it is capable of responding to the rapid transients from the ADC8860 charge kickback. 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.



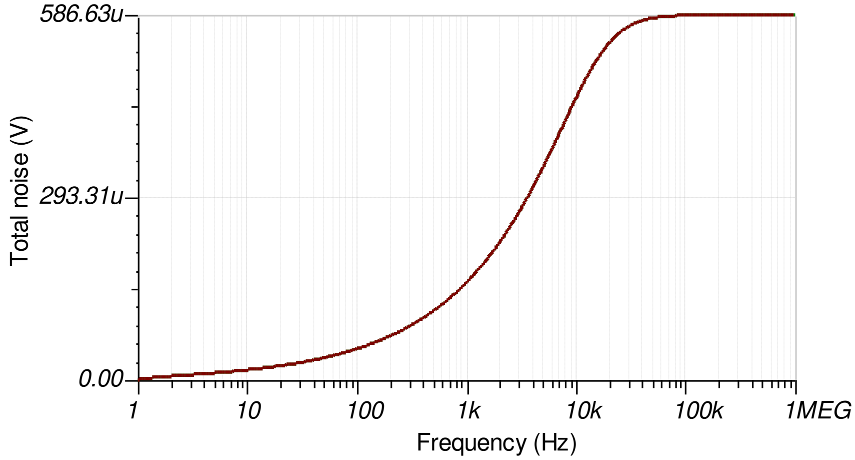
Noise Simulation

Use a simplified noise calculation for a rough estimate. We neglect the noise from the OPA192 as the instrumentation amplifier is in high gain so its noise is dominant.

$$E_n = Gain \cdot \sqrt{{e_{NI}}^2 + \left(\frac{e_{NO}}{Gain}\right)^2} \cdot \sqrt{K_n \cdot f_c}$$

$$E_n = (305.8) \cdot \sqrt{\left(18nV/\sqrt{Hz}\right)^2 + \left(\frac{110nV/\sqrt{Hz}}{305.8}\right)^2} \cdot \sqrt{1.57 \cdot (11.45kHz)} = 738\mu V/\sqrt{Hz}$$

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.

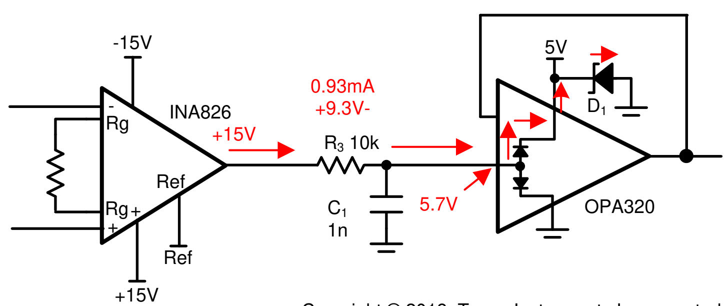


Overvoltage Protection Filter Between Instrumentation Amplifier and Op Amp

The filter between the INA826 and OPA320 serves two purposes. It protects the OPA320 from overvoltage, and acts as a noise or anti-aliasing filter. Scale the INA826 gain so that under normal circumstances, the output is inside the range of the OPA320 (that is, 0V to 5V). Thus, normally the overvoltage signals applied to the input of the OPA320 is not seen. However, during power up or in cases where the sensor is disconnected, the INA826 output can be at either power supply rail (that is, ±15V). In overvoltage cases, the resistor (R3) limits current into the OPA320 for protection. The internal ESD diodes on the OPA320 turns on during overvoltage events and direct the overvoltage signal to the positive or negative supply. In the following example, the overvoltage signal is directed to the positive supply and the transient voltage suppressor (D_1, SMAJ5.0A) turns on to sink the current. Note that the resistor is scaled to limit the current to the OPA320 absolute maximum input current (10mA). See *TI Precision Labs - Op Amps: Electrical Overstress (EOS)* for detailed theory on this subject.

$$R_3 > \frac{V_{INA} - V_{OpaSupply} - 0.7V}{I_{ABS\_MAX\_OPA}} = \frac{15V - 5.0V - 0.7V}{10mA} = 9.3k\Omega \text{ choose } 10\text{k}\Omega \text{ for margin.}$$

$$C_1 = \frac{1}{2 \cdot \pi \cdot R_3 \cdot f_c} = \frac{1}{2 \cdot \pi \cdot (10k\Omega) \cdot (15kHz)} = 1.06nF \text{ or } 1\text{nF standard value}$$



Optional Input Filter

The following figure shows a commonly used instrumentation amplifier input filter. The differential noise is filtered with C_{dif}, and the common mode noise is filtered with C_{cm1} and C_{cm2}. Note that it is recommended that $C_{dif} \geq 10C_{cm}$. This prevents conversion of common mode noise to differential noise due to component tolerances. The following filter was designed for a differential cutoff frequency of 15kHz.

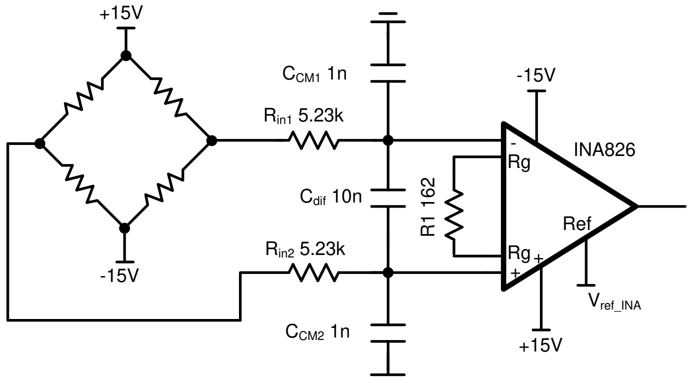
$$\text{Let } C_{dif} = 1\text{nF and } f_{dif} = 15\text{kHz}$$

$$R_{in} < \frac{1}{4 \cdot \pi \cdot f_{dif} \cdot C_{dif}} = \frac{1}{4 \cdot \pi \cdot (15kHz) \cdot (1nF)} = 5.305k\Omega \ or \ 5.23k\Omega \text{ for 1\% standard value}$$

$$C_{cm} = \frac{1}{10} \cdot C_{dif} = 100\,pF$$

$$f_{cm} = \frac{1}{2 \cdot \pi \cdot R_{in} \cdot C_{cm}} = \frac{1}{2 \cdot \pi \cdot (5.23k\Omega) \cdot (100\,pF)} = 304kHz$$

$$f_{dif} = \frac{1}{4 \cdot \pi \cdot R_{in} \cdot \left(C_{dif} + \frac{1}{2}C_{cm}\right)} = \frac{1}{4 \cdot \pi \cdot (5.23k\Omega) \cdot \left(1nF + \frac{1}{2} \cdot 100\,pF\right)} = 14.5kHz$$



Design Featured Devices

Device	Key Features	Link	Similar Devices
ADS8860	16-bit resolution, SPI, 1-Msps sample rate, single-ended input, Vref input range 2.5V to 5.0V.	16-bit, 1MSPS, 1-channel SAR ADC with single-ended input, SPI and daisy chain	Precision ADCs
OPA192	8-kHz bandwidth, Rail-to-Rail output, 450-nA supply current, unity gain stable	High-Voltage, Rail-to-Rail Input/ Output, 5µV, 0.2µV/˚C, Precision Operational Amplifier	Precision op amps (Vos<1mV)
INA826	Bandwidth 1MHz (G=1), low noise 18nV/rtHz, low offset ±40µV, low offset drift ±0.4µV/°C, low gain drift 0.1ppm/°C. (typical values)	Precision, 200-µA Supply Current, 36-V Supply Instrumentation Amplifier	Instrumentation amplifiers

Link to Key Files

Texas Instruments, source files for SBAC184, software support

Trademarks

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (March 2019) to Revision B (September 2024)	Page
• Updated the format for tables, figures, and cross-references throughout the document	1

Changes from Revision * (February 2018) to Revision A (March 2019)	Page
• Downstyle the title and changed title role to Data Converters. Added link to circuit cookbook landing page	1

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