

## Circuit for driving high-voltage SAR ADC with a buffered instrumentation amplifier

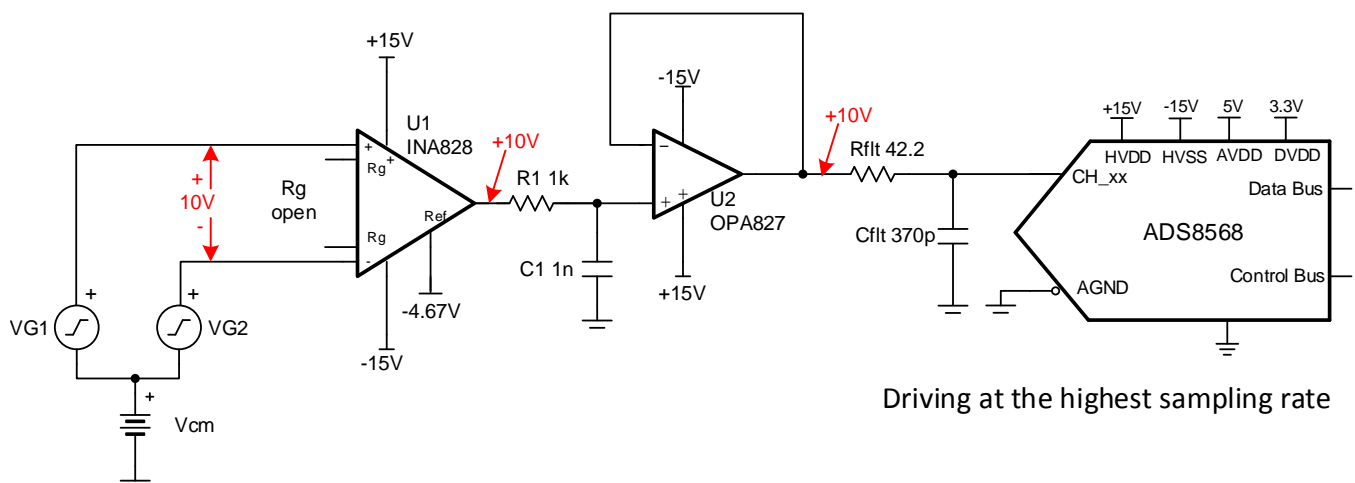
Dale Li

Input	ADC Input	Digital Output ADS7042
VinDiffMin = -10V	CH_x = -10V	8000H
VinDiffMax = +10V	CH_x = +10V	7FFFH

Power Supplies			
AVDD	DVDD	HVDD (V <sub>CC</sub> )	HVSS(V <sub>EE</sub> )
5.0V	3.3V	+15V	-15V

### Design Description

Instrumentation amplifiers are optimized for low noise, low offset, low drift, high CMRR and high accuracy but these instrument amplifiers may not be able to drive a precision ADC to settle the signal properly during the acquisition time of ADC. This design will show how a wide bandwidth buffer (OPA827) can be used with an instrumentation amplifier to achieve good settling at higher sampling rate. This INA828 instrumentation amplifier with the buffer drives the ADS8568 SAR ADC to implement data capture for a high voltage fully differential signal which may have a wide common-mode voltage range or a bipolar single-ended signal up to  $\pm 10V$ . A related cookbook circuit shows a simplified approach that does not include the wide bandwidth buffer ([Driving High Voltage SAR ADC with an Instrumentation Amplifier](#)), this simplified approach has limited sampling rate as compared to the buffered design in this document. This circuit implementation is applicable to [Industrial Transportation](#) and [Analog Input Modules](#) that require Precision Signal-Processing and Data-Conversion.



## Specifications

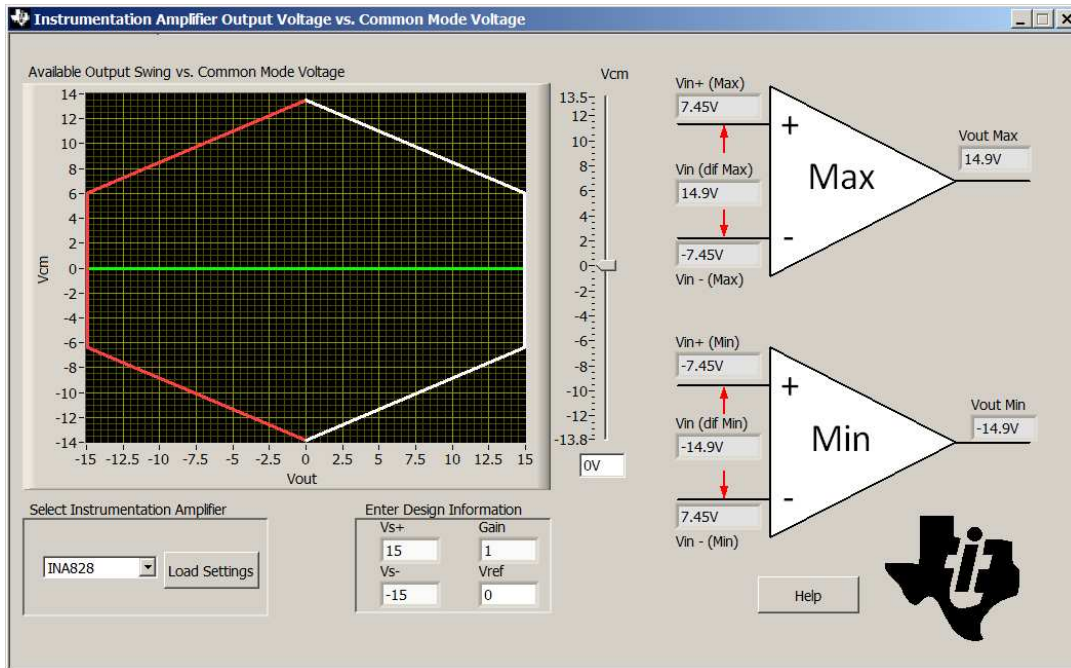
Specification	Goal	Calculated	Simulated
Transient Settling Error	< 1/2LSB (< 152 $\mu$ V)	NA	-346nV
Noise (at ADC Input)	<20 $\mu$ V <sub>RMS</sub>	47.2 $\mu$ V <sub>RMS</sub>	46 $\mu$ V <sub>RMS</sub>

## Design Notes

1. The bandwidth of instrumentation amplifiers is typically not enough to drive SAR data converters at higher data rate, so a wide bandwidth driver is needed because the SAR ADC with switched-capacitor input structure has an input capacitor that needs to be fully charged during each acquisition time. The [OPA827](#) buffer is added to allow the ADC to run at full sampling rate ([ADS8568](#) 510kSPS for parallel interface).
2. The [ADS8568](#) can accept a  $\pm 10$ -V single-ended input signal. The [INA828](#) is used to translate a  $\pm 10$ -V differential signal to a  $\pm 10$ -V single-ended signal. So the [INA282](#) is in unity gain for this example, and no external gain set resistor  $R_g$  is needed. Refer to [Circuit for Driving an ADC with an Instrumentation Amplifier in High Gain](#) in cases where the input signal range is small and gain is required.
3. Check the common mode range of the amplifier using the [Common-Mode Input Range Calculator for Instrumentation Amplifiers](#) software tool.
4. Select COG capacitors for  $C_1$  and  $C_{\text{filt}}$  to minimize distortion.
5. Precision labs video series covers the method for selecting driver amplifier and the charge bucket circuit  $R_{\text{filt}}$  and  $C_{\text{filt}}$ . For details, see the [Selecting and Verifying the Driver Amplifier](#) and [Introduction of SAR ADC Front-End Component Selection](#) videos.
6. Set the cutoff of the filter between the op amp and instrumentation amplifier for anti aliasing and to minimize noise. See [Aliasing and Anti-aliasing Filters](#) for more details on aliasing and anti-aliasing filters.

### Component Selection

1. Find the gain based on differential input signal and ADC full-scale input range. The input signal in this design is  $\pm 10\text{-V}$  high voltage signal, so the Gain of [INA828](#) should be set to 1 and no gain resistor ( $R_g$ ) is needed.
2. Use the [Common-Mode Input Range Calculator for Instrumentation Amplifiers](#) to determine if the [INA828](#) is violating the common mode range. The common mode calculator in the following figure indicates that the output swing is  $\pm 14.9\text{V}$  for a  $0\text{-V}$  common-mode input.

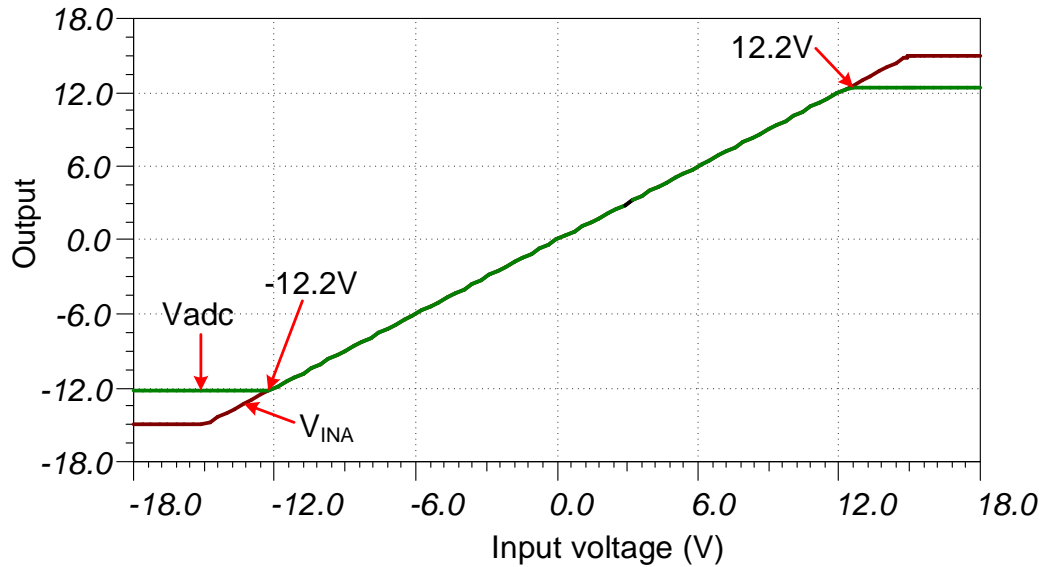


3. Find the value for  $C_{filt}$ , and  $R_{filt}$  using [TINA SPICE](#) and the methods described in [SAR ADC Front-End Component Selection](#). The value of  $R_{filt}$  and  $C_{filt}$  shown in this document will work for these circuits; however, if you use different amplifiers you will have to use TINA SPICE to find new values.
4. Select the RC filter between the [INA828](#) and [OPA827](#) based on your system requirements ( $f_{cRC} = 15.9\text{kHz}$  in this example). Set the cutoff of this filter for anti aliasing and to minimize noise.

$$f_{cRC} = \frac{1}{2\pi \cdot R_1 \cdot C_1} = \frac{1}{2\pi \cdot (1\text{k}\Omega) \cdot (1\text{pF})} = 159\text{kHz}$$

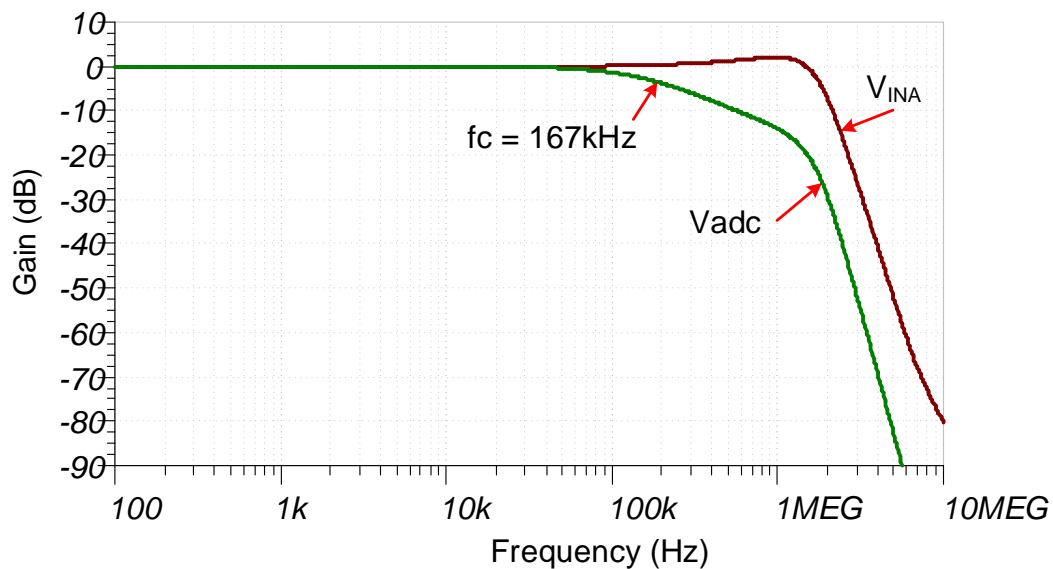
### DC Transfer Characteristics

The following graph shows a linear output response for inputs from differential  $-12.2\text{V}$  to  $+12.2\text{V}$ . The input range of the ADC is  $\pm 10\text{V}$ , so the amplifiers are linear well beyond the required range. Refer to [Determining a SAR ADC's Linear Range when using Instrumentation Amplifiers](#) for detailed theory on this subject. The full-scale range (FSR) of the ADC falls within the linear range of the Instrumentation Amplifier.



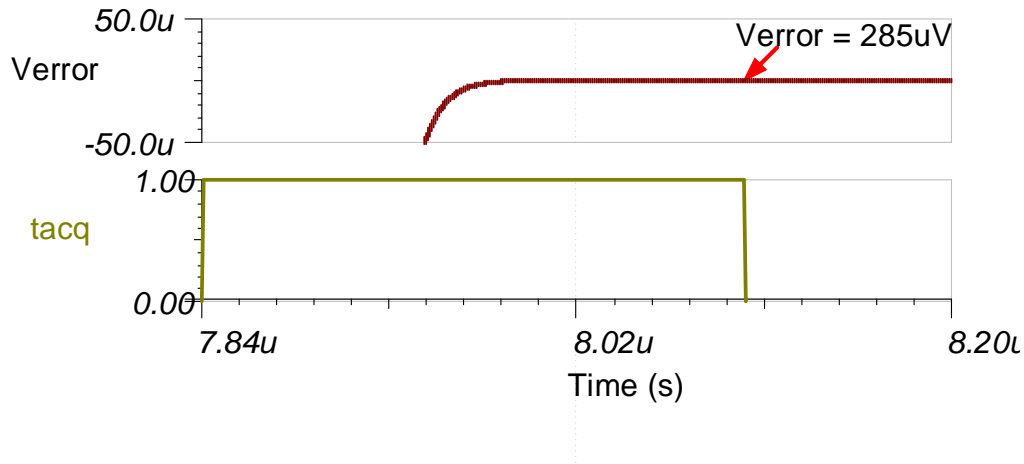
### AC Transfer Characteristics

The bandwidth for this system is simulated to be  $167\text{kHz}$  and the gain is  $0\text{dB}$ . The filter between the [OPA827](#) and [INA828](#) limits the bandwidth to about  $167\text{kHz}$ .



### Transient ADC Input Settling Simulation (510kSPS)

The [OPA827](#) buffer (22MHz GBW) is used because it is capable of responding to the rapid transients from the [ADS8568](#)'s charge kickback. The op amp buffer allows the system to achieve the [ADS8568](#) maximum sampling rate of 510kSPS. The following simulation shows settling to a full scale DC input signal with [INA828](#) and [OPA827](#) buffer, and [ADS8568](#). This type of simulation shows that the sample and hold kickback circuit is properly selected to meet desired  $\frac{1}{2}$  of a LSB (152 $\mu$ V). Refer to the [Introduction to SAR ADC Front-End Component Selection](#) training video series for detailed theory on this subject.



## Noise Simulation

The section walks through a simplified noise calculation for a rough estimate. We include both the [INA828](#), and [OPA827](#) noise. Note that the RC filter between the instrumentation amplifier and op amp significantly reduces the total noise. The output filter pole is estimated as a second order filter because the [OPA827](#) (22MHz) bandwidth limit and charge bucket filter cutoff frequency (10.2MHz) is close.

$$E_{n-INA} = G \sqrt{e_{n-in}^2 + \left(\frac{e_{n-out}}{G}\right)^2} \cdot \sqrt{K_n \cdot f_{cRC}}$$

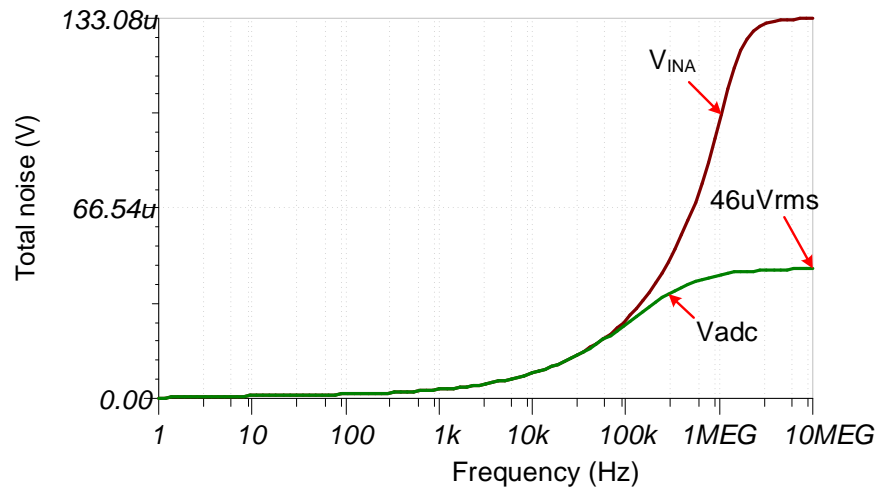
$$E_{n-INA} = 1 \sqrt{\left(4 \text{ nV}/\sqrt{\text{Hz}}\right)^2 + \left(\frac{90 \text{ nV}/\sqrt{\text{Hz}}}{1}\right)^2} \cdot \sqrt{(1.57) \cdot (159 \text{ kHz})} = 45.1 \mu\text{Vrms}$$

$$f_{c-adcFilter} = \frac{1}{2\pi \cdot R_{filt} \cdot C_{filt}} = \frac{1}{2\pi \cdot (42.2\Omega) \cdot (370 \text{ pF})} = 10.2 \text{ MHz}$$

$$E_{opa} = e_{n-opa} \sqrt{K_n \cdot f_c} = (4 \text{ nV}/\sqrt{\text{Hz}}) \sqrt{(1.22) \cdot (10.2 \text{ MHz})} = 14.1 \mu\text{Vrms}$$

$$E_{n-total} = \sqrt{E_{n-INA}^2 + E_{opa}^2} = \sqrt{(45.1 \mu\text{V})^2 + (14.1 \mu\text{V})^2} = 47.2 \mu\text{Vrms}$$

Note that calculated and simulated match well (calculated = 47.2μV, Simulated = 46μV). See [TI Precision Labs - Noise 4](#) for detailed theory on amplifier noise calculations, and [Calculating Total Noise for ADC Systems](#) for data converter noise.



## Design Featured Devices

Device	Key Features	Link	Similar Devices
<a href="http://www.ti.com/product/ADS8568">ADS8568</a>	16-bit, 8 Channel Simultaneous-Sampling, Bipolar-Input SAR ADC	<a href="http://www.ti.com/product/ADS8568">http://www.ti.com/product/ADS8568</a>	<a href="http://www.ti.com/adcs">www.ti.com/adcs</a>
<a href="http://www.ti.com/product/INA828">INA828</a>	Bandwidth 1MHz (G=1), low noise 18nV/rtHz, low offset $\pm 40\mu\text{V}$ , low offset drift $\pm 0.4\mu\text{V}/^\circ\text{C}$ , low gain drift 0.1ppm/ $^\circ\text{C}$ . (Typical values)	<a href="http://www.ti.com/product/INA828">http://www.ti.com/product/INA828</a>	<a href="http://www.ti.com/inas">www.ti.com/inas</a>
<a href="http://www.ti.com/product/OPA827">OPA827</a>	Gain bandwidth 22MHz, low noise 4nV/rtHz, low offset $\pm 75\mu\text{V}$ , low offset drift $\pm 0.1\mu\text{V}/^\circ\text{C}$ (Typical values)	<a href="http://www.ti.com/product/OPA827">http://www.ti.com/product/OPA827</a>	<a href="http://www.ti.com/opamp">www.ti.com/opamp</a>

### Design References

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

### Links to Key Files

Source files for this circuit - <http://www.ti.com/lit/zip/SBAC216>.

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