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# EXPLORING DIFFERENT SAR ADC ANALOG INPUT ARCHITECTURES

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Successive approximation register analog-to-digital converters, better known as SAR ADCs, are a versatile class of analog-to-digital converters that produce a digital (discrete time) representation of a continuous analog waveform. They accomplish this task via a process of charge redistribution where known fixed quantities of charge are compared to an acquired charge from the input to the ADC. During this process, a binary search is performed through all possible digital codes (quantization levels) where the end result converges on a code that brings the internally housed comparator back into balance. The combination of ones and zeros represents the decision sequence generated by the circuit that brought the system back to an equilibrium state.

From a high level, the SAR ADC is a versatile, easy to use, completely asynchronous data converter. Still, there are some choices that need to be made when deciding which converter is to be used for a particular application. Here specifically, we will focus on the analog input signal types that are available within the Analog Devices SAR ADC product portfolio. It should be noted that even though the focus is on SAR ADCs, the input types are universal to all ADC architectures. Depending upon the source type or the overall goals of the circuit under consideration, certain design decisions and trade-offs will need to be made. The simplest solution would be to match the ADC input type to the signal source output configuration. However, the source signal may require conditioning that changes the signal type or there could be cost, power, or area considerations that influence analog input type decisions. Let's explore the different available analog input types.

## Single-Ended

The simplest analog input type is the single-ended input. In this case, only one wire is required to get a signal from the source to the ADC. There will be a single input pin with no direct return or sense path back to the signal source. The conversion result will be generated with respect to the ground pin of the ADC. Depending upon the specific device, the input may either be unipolar or bipolar. In the single-ended case, simplicity is its merit. Only one trace is required to get a signal from its source to the ADC. This can reduce the complexity of a system while lowering the power dissipation of the overall signal chain. There is potentially a trade-off for this simplicity. A single-ended setup does not reject dc offsets that are present within the signal chain. The single-ended system relies upon making measurements relative to a current carrying ground plane and voltage differences between the source ground and ADC ground will appear in the conversion results. As well, the setup is more susceptible

to coupled noise. Therefore, the signal source and the ADC should be kept close together to mitigate these effects. If the SAR ADC is a unipolar single-ended configuration, the allowable signal swing is between ground and positive full scale, which is typically set by the ADC reference input. A visual representation of a single-ended unipolar input can be seen in Figure 1. Devices with a single-ended unipolar input include the [AD7091R](#) and the [AD7091R-8](#).

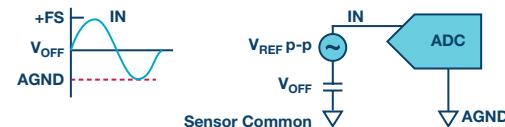


Figure 1. Unipolar single-ended.

If the SAR ADC is a bipolar single-ended configuration, the allowable signal swing is between positive full scale and negative full scale relative to ground. Again, full scale is typically set by the ADC reference input. A visual representation of a single-ended bipolar input can be seen in Figure 2. A device with a single-ended bipolar input is the [AD7656A-1](#).



Figure 2. Bipolar single-ended.

## Pseudo Differential

If the need arises to sense the signal ground or decouple the relative measurement result from the current carrying ground plane, the signal chain designer may want to consider a move to a pseudo differential input structure. A pseudo differential device is essentially a single-ended ADC with a ground sense. The device is performing a differential measurement, but the differential that is sensed is a single-ended input signal measured with respect to the input signal ground level. The single-ended input is driven onto the positive input (IN+) of the ADC and the input ground level is driven onto the negative input (IN-) of the ADC. One thing to note is the signal chain designer must pay attention to the analog input range of the negative input. In some cases, the negative input pin has a limited input range compared to the positive input. In these cases, the positive input can freely swing through the allowable input voltage range, while the negative input to the ADC may be restricted to some smaller  $\pm$  voltage range around ADC ground. The allowable input ranges for each ADC input can be found in the data sheet. Look for a specification named absolute input voltage, as seen in Figure 3.

Parameter	Conditions	A Grade			B Grade			Unit
		Min	Typ	Max	Min	Typ	Max	
Resolution		16			16			Bits
Analog Input Voltage Range	IN+ – (IN–)	0		$V_{REF}$	0		$V_{REF}$	V
Absolute Input Voltage	IN+, IN–	-0.1		$V_{REF} + 0.1$	-0.1		$V_{REF} + 0.1$	V
IN+, IN–	-0.1		+0.1	-0.1		+0.1		V
Analog Input CMRR	$f_{IN} = 250$ kHz	60			60			dB

Figure 3. Absolute input voltage example.

If a pseudo differential device with limited IN– voltage range, such as the [AD7980](#), needs to reject undesired signals greater than the absolute input voltage range, the signal chain designer may need to consider an instrumentation amplifier to remove these larger common modes before presenting the signal to the ADC. There are three configurations of pseudo differential: unipolar, pseudo bipolar, and true bipolar. The ADI SAR ADC portfolio offers devices that provide each configuration. In a unipolar pseudo differential setup, a single-ended unipolar signal is driven onto the positive input of the ADC and the signal source ground is driven onto the negative ADC input, as seen in Figure 4. Examples of devices with a unipolar pseudo differential input include the [AD7980](#) and the [AD7988-5](#).

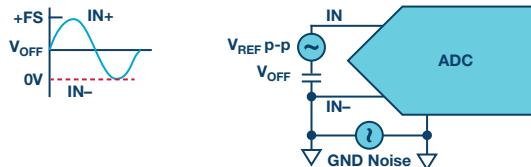


Figure 4. Unipolar pseudo differential.

In a pseudo bipolar setup, a single-ended unipolar signal is driven onto the positive input of the ADC. However, instead of the signal source ground driven onto the negative ADC input, this input sees half of the full-scale voltage. In this case, the input range would be considered  $\pm V_{FS}/2$  instead of 0 to  $V_{FS}$ . There has been no dynamic range increase, the difference between the unipolar case and the pseudo bipolar case is what the positive input is measured against. As with the unipolar pseudo differential case, the pseudo bipolar negative input has a limited input range. However, now it's  $\pm$  some voltage about  $V_{FS}/2$  rather than ground. The pseudo bipolar input range diagram can be seen in Figure 5. In this case,  $V_{OFF} = V_{FS}/2$ . An example of a device with a pseudo bipolar input option is the [AD7689](#).

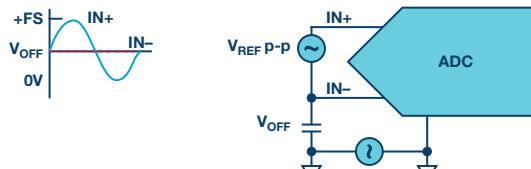


Figure 5. Pseudo bipolar.

The pseudo differential true bipolar case operates much like the unipolar pseudo differential case except that the single-ended positive ADC input can swing above and below ground. Usually the peak-to-peak input range is twice the reference voltage or some multiple of this ratio. For example, if the reference voltage is 5 V, then a pseudo differential true bipolar device may accept inputs in the range of  $\pm 5$  V. Figure 6 shows the pseudo

differential true bipolar input range diagram. An example of a device with a pseudo differential true bipolar input is the [AD7606](#).

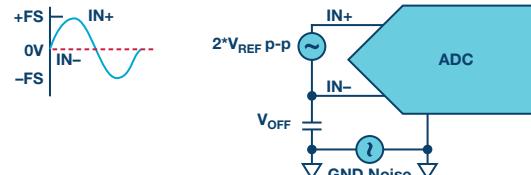


Figure 6. Pseudo differential true bipolar.

## Differential

The pseudo differential architecture has the advantage over single-ended architecture by being able to reject certain perturbing signals within the conversion system. However, there is an architecture that can offer the same rejection benefits while also increasing the dynamic range of the system. Differential architecture allows the user to maximize the input range of the ADC. Compared to a single-ended or pseudo differential scheme, differential signaling provides the ability to double the input range for a given supply and reference setup, providing up to a 6 dB increase in dynamic range without increasing the device power consumption.

ADI offers two types of devices with differential inputs. The first type covered here is differential antiphase. In this case, the ADC is converting the difference between the positive and negative inputs of the ADC while the positive and negative inputs are swinging 180° out of phase with respect to each other. Typically, differential antiphase devices are unipolar. Therefore, each leg of the differential will swing between ground and positive full scale, which is set by the reference input. As a result of the legs of the differential being 180° out of phase, the common mode of the inputs is fixed. Just like the pseudo differential devices, differential antiphase devices can have a restriction on their allowable common-mode input range. This range can be found in the specification table of the product data sheet, as seen in Figure 7. For a device where the absolute input range of either ADC input is 0 volts to positive full scale, the common-mode voltage would be  $V_{FS}/2$ . In most cases, for high resolution (16 bits and greater) differential antiphase SAR ADCs, the common-mode voltage range is  $\pm 100$  mV around the typical common-mode voltage.

Differential antiphase devices are usually chosen when the absolute best performance is desired. Differential signaling will provide a maximum noise rejection and it tends to cancel out even ordered distortion characteristics. As seen in Figure 8, with the legs of the differential swinging in opposing directions, the dynamic range and SNR are improved with respect to single-ended and pseudo differential configurations.

Parameter	Conditions	Min	Typ	Max	Units
Analog Input Voltage Range	IN+ – (IN–)				V
IN+, IN–		$-V_{REF}$		$+V_{REF}$	V
Absolute Input Voltage	IN+, IN–	-0.1		$V_{REF} + 0.1$	V
Common-Mode Input Range	$f_{IN} = 250$ kHz	$-V_{REF}/2 - 0.1$	$-V_{REF}/2$	$V_{REF}/2 + 0.1$	dB
Analog Input CMRR			65		

Figure 7. Differential common-mode input range.

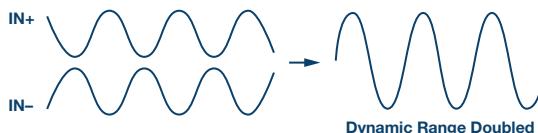


Figure 8. Dynamic range increase from differential signaling.

If it's desired to maximize system performance in a signal chain where the signal source is single-ended, a single-ended-to-differential amplifier, such as the [ADA4940-1](#) or the [ADA4941-1](#), can be used to properly condition the input signal and match the common mode to that of the ADC. As with the pseudo differential devices, if large common modes are present in the system, an instrumentation amp should be used to condition the bulk of the common mode. The differential ADC can handle fine changes in common mode and the aggregate signal chain will have excellent CMRR. Figure 9 shows the differential antiphase input range diagram. Examples of devices with a differential antiphase inputs are the [AD7982](#), [AD7989-5](#), and the [AD7915](#).

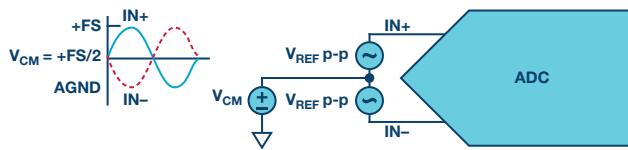


Figure 9. Differential antiphase.

The common-mode range restriction is necessary to achieve optimal performance and to not negatively impact converter dynamic range. There are some common errors that have been observed when operating the differential antiphase devices that will violate the common-mode range. Figure 10 shows a user error that is frequently produced when implementing a differential antiphase device. In this scenario, the differential signals are not  $180^\circ$  out of phase. As a result of this, the common mode is varying wildly between the two ADC input pins and is in violation of the data sheet for parts that operate under the constraints of Figure 7.

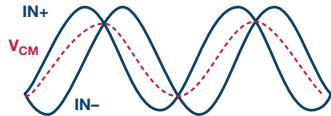


Figure 10. Common-mode violation.

Other common differential antiphase mistakes that are seen include signals that are  $180^\circ$  out of phase, but at an improper common mode or having the IN- pin of the ADC connected to a dc pedestal voltage. Providing a dc voltage at the negative ADC input will quickly violate the common-mode range specification and also removes the dynamic range advantage of differential signaling. The second type of differential signaling is measuring the differential between any two signals regardless of common mode. ADI provides a family of integrated data acquisition solutions based upon SAR ADC technology that measures a fully differential signal. For signal chain designers that are looking for an integrated data acquisition solution with wide allowable input common-mode range, ADI offers the [ADAS3022](#) and the [ADAS3023](#). These are bipolar sequential and simultaneous sampling data acquisition systems, respectively, that feature a common-mode range as wide as  $\pm 10$  V. Within this range, they have the ability to represent the difference between any two signals.

The analog input type can influence the digital output encoding. Converters that feature a unipolar input range, such as single-ended unipolar and pseudo differential, will feature a straight binary encoding.

Code 0 will represent a negative full-scale input voltage and code  $2N - 1$  (where N is the number of bits) will represent a positive full-scale input. Devices that have an input with a  $\pm$  polarity will feature two's complement encoding so that a sign bit can be presented to the user. Devices with a  $\pm$  polarity include single-ended bipolar, pseudo differential bipolar, pseudo bipolar, and all differential devices. For these ADCs, the negative full-scale input will be represented by code  $-2N - 1$  and the positive full-scale input is represented by code  $2N - 1 - 1$ .

The SAR ADC is a versatile, low power, high performance option for creating an analog-to-digital conversion signal chain. These devices are very easy to implement. However, to get the desired performance out of the system, certain architecture choices must be made. Here we have specifically focused on the analog input type selections that are available in the Analog Devices SAR ADC portfolio. Each input type provides certain benefits that must be compared against particular trade-offs. As previously described, making the correct selection is crucial to achieving optimal performance.

For information on selecting the correct driver amplifier configuration, please refer to the following link: [Single/Dual Amplifier Configurations for Driving Unipolar Precision ADCs](#).

For information on properly selecting the ADC driver for a given application, please refer to the following link: [Front-End Amplifier and RC Filter Design for a Precision SAR Analog-to-Digital Converter](#).

## About the Author

Ryan Curran [[ryan.curran@analog.com](mailto:ryan.curran@analog.com)] is a product applications engineer within the Precision Converters business unit at Analog Devices. He joined ADI in 2005 and has focused on SAR ADCs since joining the company. Ryan received his B.S.E.E. from the University of Maine in Orono, ME, and is currently pursuing an M.B.A. from the Isenberg School of Management at UMass Amherst.

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