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Application Note Abstract

This application note describes the different ways of implementing an instrumentation amplifier using the PSoC® 3 device.

Introduction: Instrumentation Amplifiers

Instrumentation amplifiers are useful in applications where a small differential signal riding on a big common mode signal needs to be amplified and a single ended output is desired. PSoC 3 device with its opamps and SC/CT blocks can implement instrumentation amplifier with four external resistors.

In applications where a single ended output is not desired, PSoC 3 offers the easiest solution for instrumentation applications, the delta sigma ADC. The delta sigma ADC which includes a differential amplifier front-end by itself can take care of most instrumentation needs. Refer to [Differential Amplifier with Differential ADC](#) on page 4, for information on digital processing of differential signal.

Characteristics of an Instrumentation Amplifier

This section discusses some of the characteristics of instrumentation amplifiers.

Common Mode Rejection Ratio

The Common Mode Rejection Ratio (CMRR) determines the ability of an instrumentation amplifier to ignore the common mode signals (average of the two input signals) and amplify the differential signals (difference of the two input signals). Mathematically,

$$\text{CMRR} = 20 * \log \left(\frac{A_d}{A_c} \right) \quad \text{Equation 1}$$

Where,

Ad is the differential gain

Ac is the common mode gain

Ideally, the common mode gain is expected to be zero and CMRR is expected to be infinity

Input Impedance

The instrumentation amplifier gets its input from sources with a finite output resistance. High input impedance is desired to ensure that the source is not loaded and the accuracy of the measurement is not affected.

Input Common Mode Range

Input Common Mode Range (ICMR) is the range of common mode input through which the instrumentation amplifier operates unsaturated.

Input Offset Voltage

Input offset voltage is differential voltage that must be applied to the differential amplifier input to make the output voltage zero. Ideally, offset is expected to be zero volts.

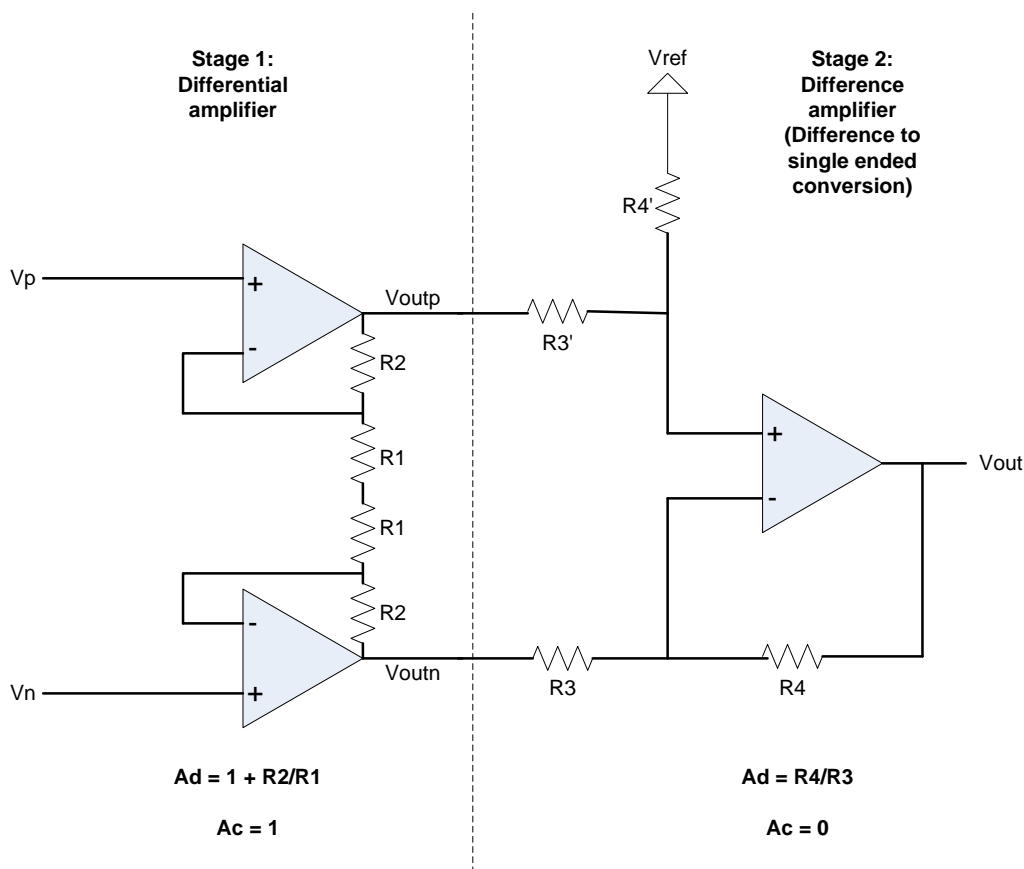
Instrumentation Amplifier Implementation

Instrumentation amplifier can be implemented in multiple ways. This section discusses two ways along with the PSoC 3 implementation. As mentioned earlier, a third way is also discussed which can be used if you need digital processing of the differential signal.

Classical Three Opamp Instrumentation Amplifier

The classical three opamp instrumentation amplifier is a popular topology for its high input impedance and CMRR (see [Figure 1](#) on page 2). It has two stages: the differential amplifier and difference amplifier. The differential amplifier stage provides high input impedance and common mode rejection. The difference amplifier stage nulls the common mode signal and provides the differential to single ended conversion.

Figure 1. Classical Three Opamp Instrumentation Amplifier



The differential output voltages of the differential amplifier are given by,

$$V_{outp} = V_n + (V_p - V_n) * \left(1 + \frac{R_2}{2R_1}\right) \quad \text{Equation 2}$$

$$V_{outn} = V_p + (V_n - V_p) * \left(1 + \frac{R_2}{2R_1}\right) \quad \text{Equation 3}$$

$$V_{outp} - V_{outn} = (V_p - V_n) * \left(1 + \frac{R_2}{R_1}\right) \quad \text{Equation 4}$$

Expressing V_{outp} and V_{outn} in terms of differential (V_d) and common mode signals (V_c), you get,

$$V_{outp} = V_c + \frac{V_d}{2} \left(1 + \frac{R_2}{R_1}\right) \quad \text{Equation 5}$$

$$V_{outn} = V_c - \frac{V_d}{2} \left(1 + \frac{R_2}{R_1}\right) \quad \text{Equation 6}$$

Where,

$$V_c = \frac{V_p + V_n}{2} \text{ and } V_d = V_p - V_n$$

The second differential amplifier is governed by,

$$V_{out} = \frac{R_4}{R_3} * (V_{outp} - V_{outn}) \quad \text{Equation 7}$$

CMRR

The classical three opamp instrumentation amplifier achieves an excellent common mode rejection in the first stage. It provides a high differential gain and unity common mode gain without precise matching of resistors R_1 and R_2 . The second difference amplifier stage nulls the common mode achieving high CMRR. However, this requires the resistors R_3 and R_3' , R_4 and R_4' to be precisely matched, making the CMRR dependent on the resistor matching.

Input Impedance

The input impedance is very high as the signal enters the non-inverting terminal of the opamp.

ICMR

The input common mode range is governed by Equation 5 and Equation 6. V_{outp} or V_{outn} should not saturate and a lower gain on the first stage helps in a higher ICMR.

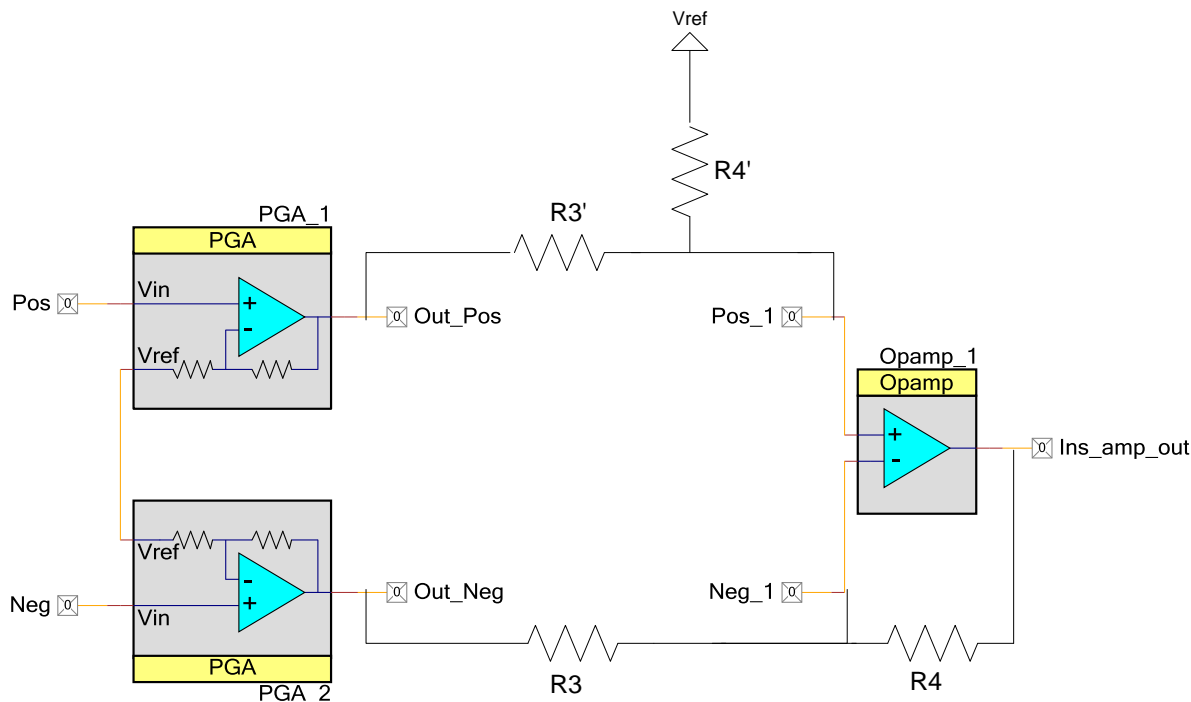
Equation 2 through 6 completely govern the voltages at all intermediate and output nodes and should be used to determine the maximum differential voltage without saturating the opamps. The DC output level is fixed by V_{ref} shown in Figure 1.

PSoC 3 Implementation

In PSoC 3, the classical three opamp instrumentation amplifier can be implemented as shown in Figure 2 with four external resistors. Two PGAs combined back-to-back implements the front end differential amplifier. An opamp implements the difference amplifier with four resistors of the

difference amplifier used externally. The gain of both PGAs should be set to the same value and this determines the first stage differential gain, which can be a maximum of 50. The ratio of the resistors R3 and R4 determine the second stage differential gain.

Figure 2. Top Design of Classical Three Opamp Instrumentation Amplifier



Two Opamp Topology

The two opamp instrumentation amplifier uses two non inverting amplifiers as shown in Figure 3 on page 4. Its behavior is governed by the equation,

$$V_{out} = V_p * \left(1 + \frac{R_{f2}}{R_2}\right) - V_n \left(1 + \frac{R_{f1}}{R_1}\right) \left(\frac{R_{f2}}{R_2}\right) \quad \text{Equation 8}$$

When the input to feedback resistor ratio of the first opamp is the inverse of the second, it behaves similar to an instrumentation amplifier.

$$\frac{R_{f1}}{R_{in1}} = \frac{R_{in2}}{R_{f2}} \quad \text{Equation 9}$$

In this case, Equation 8 becomes,

$$V_{out} = (V_p - V_n) * \left(1 + \frac{R_{f2}}{R_2}\right) \quad \text{Equation 9}$$

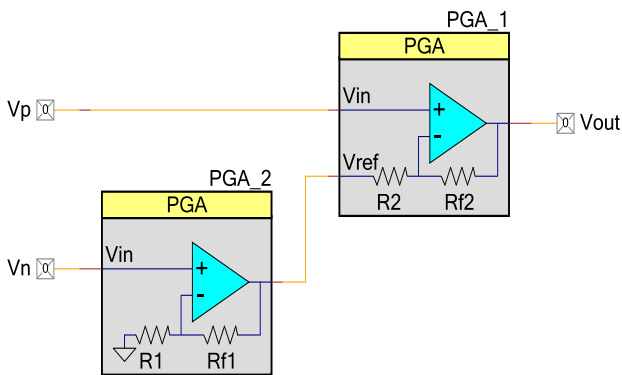
The PSoC 3 implementation using PGAs is shown in Figure 3 on page 4. The mentioned ratio requirement is satisfied only for a PGA gain of 2. Therefore, an instrumentation amplifier having a gain of only two can be implemented with the Two Opamp Topology method with PSoC 3 PGAs. For higher gains, a third PGA should be used. The Two Opamp Topology can also be realized with two naked opamps and four external resistors. In this case, the instrumentation amplifier does not have any gain limitation.

The CMRR is dependent on matching of the resistor ratios.

The input impedance is very high as the inputs are driven into non-inverting terminals of opamps.

The ICMR is directly related to gain as governed by Equation 8. Higher gain instrumentation amplifiers have a better input range.

Figure 3. Two Opamp Topology



Differential Amplifier with Differential ADC

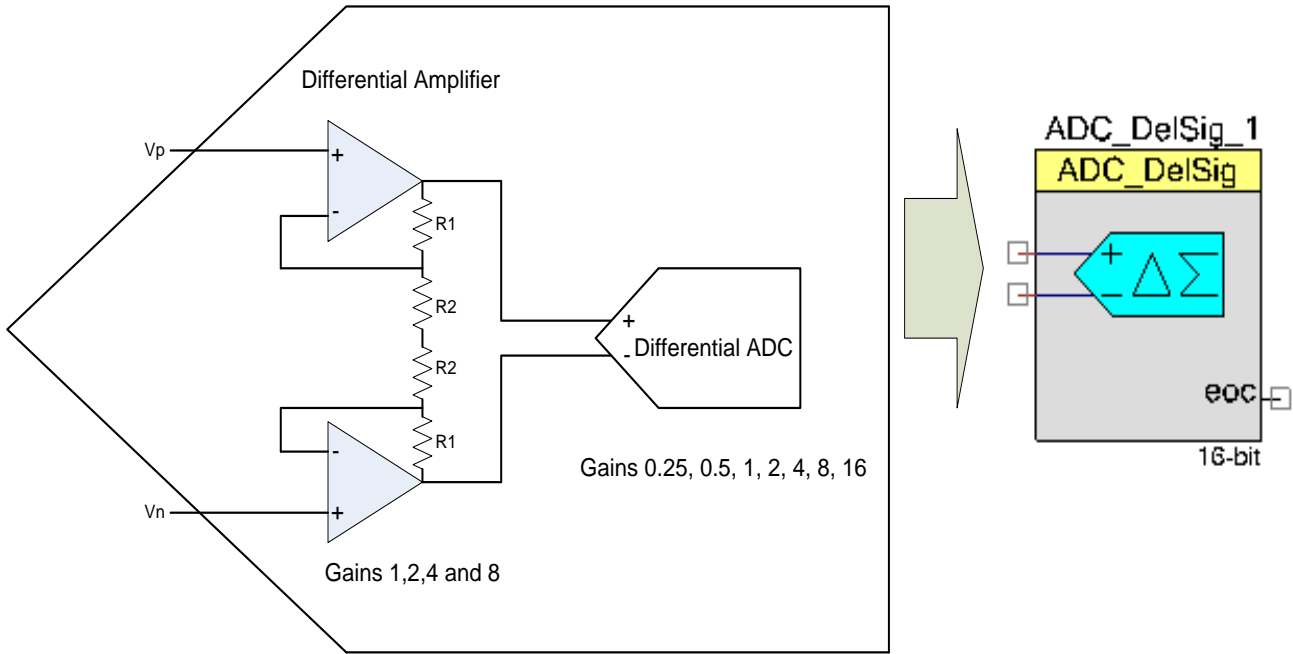
In instrumentation applications where a single ended output is not desired and the output needs to be digitally post-processed, the PSoC 3 ADC alone suffices. The PSoC 3 ADC has a differential amplifier front end which provides very high input impedance and CMRR. It can

have gains up to 8 and the differential ADC can provide gains up to 16. The differential amplifier gain is set using the Input Buffer gain parameter in the ADC configuration window. The gain of the ADC is set using the input range selection parameter. The following table shows the details. In total, you can have a gain of 128 with the ADC. The CMRR is high, equal to 90 dB; the input offset voltage is low less than 100 μ V.

Input Range	ADC Gain
-Input $\pm 4 \cdot V_{ref}$	0.25
-Input $\pm 2 \cdot V_{ref}$	0.50
-Input $\pm V_{ref}$	1.00
-Input $\pm 0.5 \cdot V_{ref}$	2.00
-Input $\pm 0.25 \cdot V_{ref}$	4.00
-Input $\pm 0.125 \cdot V_{ref}$	8.00
-Input $\pm 0.0625 \cdot V_{ref}$	16.00

Most applications generally fall under this category and PSoC 3 can accurately process such differential inputs with 20 bit resolution and a high gain of 128.

Figure 4. PSoC 3 Delta Sigma ADC (Differential Amplifier and Differential ADC)



Summary

PSoC 3 and PSoC 5 devices' PGAs and opamps allow easy construction of instrumentation amplifiers. However, most instrumentation amplifier needs can easily be satisfied within the PSoC 3 ADC which offers high CMRR, input impedance, low offset, and very high gain.

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Document History

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**	2896211	PFZ	03/29/10	New Application note.
*A	2922704	PFZ	04/26/10	Updated Figure 1. Minor Text edits

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