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ABSTRACT

Type-2 programmable gain amplifier (PGA) module incorporates an operational amplifier (op-amp) with an internal adjustable gain that can be changed from 2V/V to 64V/V. Due to the PGA's high-input impedance, wide bandwidth, and low output impedance, the PGA offers a buffer operational mode that can present load isolation at the output of the buffer. Having fully differential and rail-to-rail inputs allow the PGA module to easily interface a wide range of input signals and fit them to the low-voltage domain of analog-to-digital converters (ADC). These features make the PGA module a high-performance analog front-end for various applications. This application note describes the functionality of the PGA module in all devices with a Type-2 PGA module, and how the module can be used for analog signal conditioning and acquisition in real-time control applications. For more information on peripheral types, see the [C2000 Real-Time Control MCU Peripherals](#) reference guide.

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1 Introduction

The integrated PGA helps to reduce cost and design effort for many control applications that traditionally require external, standalone amplifiers. On-chip integration makes sure the PGA is compatible with the downstream analog-to-digital converter (ADC) and comparator subsystem (CMPSS) modules. Software-selectable gain, filter settings, and different operational modes make the PGA adaptable to various performance needs. The PGA module provides a desired gain when an input signal has insufficient amplitude. The PGA module can be placed in front of a comparator or ADC to increase the signal's amplitude.

Type-1 and Type-2 PGAs offer adjustable gain values to amplify the input signal but have some key differences.

- **Operation modes:** Type-1 PGA only supports non-inverting mode, while Type-2 PGA can support buffer, standalone, non-inverting, and subtracting operation modes. Please note that Type-2 PGA module can operate as a unity-gain amplifier to drive the input circuit of a successive approximation-register (SAR) ADC.
- **Gain range:** Type-1 PGA only provides 3x to 24x voltage gain, while Type-2 PGA offers programmable gain values of 2x to 64x. The wide gain range makes Type-2 PGA a good choice for various applications.
- **Low-pass filtering:** In Type-2 PGA, two different low-pass filters can be implemented using either the embedded filter resistor or the gain resistor. The gain resistor, in combination with an external capacitor, helps the more stable operation of the PGA modules.

1.1 Supplementary Information

For more information on the PGA module on a specific C2000™ device, see the device-specific data sheet and the corresponding technical reference manual (TRM). This application note was written using the F28P55x family of devices. The data sheet and TRM used for this application note include:

- TMS320F28P55x Real-Time Controllers technical reference manual
- TMS320F28P55x Real-Time Controllers data sheet

Additional support is provided by the [TI E2E™](#) design support forums.

1.2 Features

Features available to PGA modules include:

- Rail-to-rail input and output voltage within VDDA and VSSA range
- Programmable gain modes, including unity gain and other values from 2X - 64X
- Standalone gain mode using off-chip passive components
- Post-gain filtering using on-chip resistors and off-chip capacitor
- Differential input support
- Hardware-assisted chopping for offset reduction, which enables higher-precision measurements at low currents and allowing the use of smaller value shunt resistors for improved system efficiency.
- No PGA_INM pin connection is needed if using the internal connection to VSSA
- Support for Kelvin ground connections using PGA_INM pins
- The temperature stability is one of the key advantages of on-chip PGAs over discrete implementations as integrating the amplifier with all the gain-setting resistors enables slight and unified temperature drift.

1.3 Block Diagram

[Figure 1-1](#) shows the block diagram of the PGA module. The active component in the PGA is an embedded op-amp that can be configured as a non-inverting or inverting amplifier with internal feedback resistors. These internal feedback resistor values are paired to produce software-selectable voltage gains. Bringing these gain resistors internal to the device increases matching and temperature drift stability compared to the typical external gain-setting resistors.

Three PGA signals are available at the device pins:

- PGA_INP is the positive input to the PGA op-amp.
- PGA_INM is the negative input to the PGA op-amp.
- PGA_OUT supports op-amp output filtering with RC components. The filtered signal is available for sampling and monitoring by the on-chip ADC and CMPSS modules. For more information, see the device data manual.

Please note that PGA_OUT_INT is an internal signal at the op-amp output, which is available for sampling and monitoring by the internal ADC and CMPSS modules.

Analog pins and internal connection for the device are given in the Analog Subsystem chapter of the Technical Reference Manual.

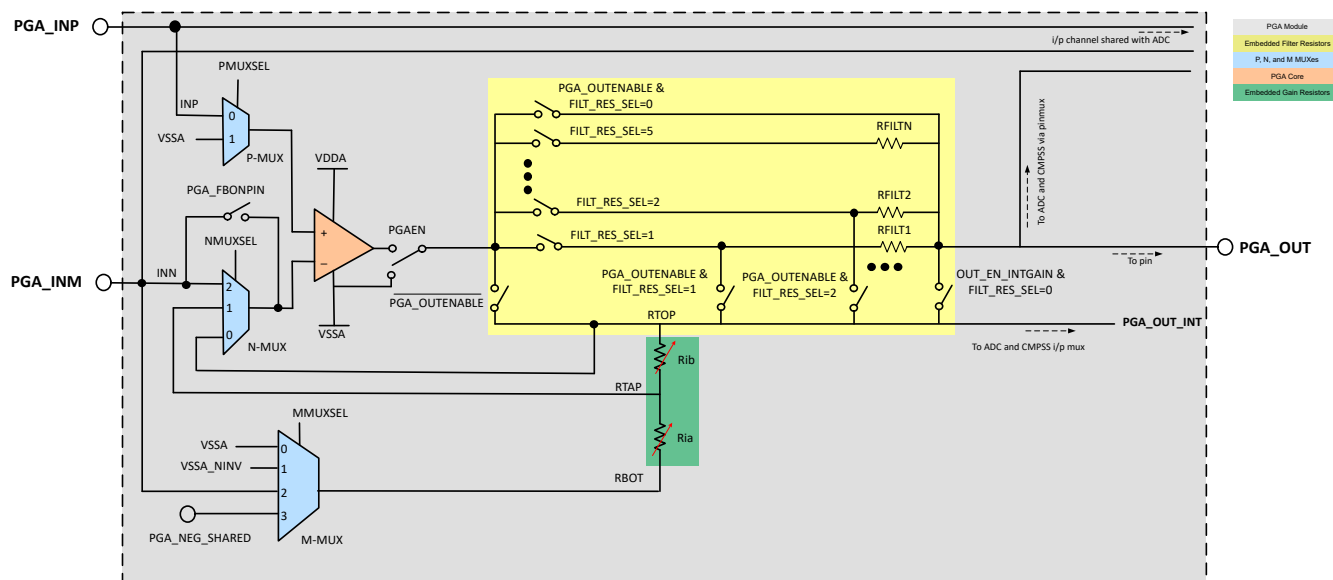


Figure 1-1. PGA Module Block Diagram

1.4 Operation Modes

PGA module can support four different operational modes based on the values of the MUXSEL register, which are given in Table 1-1.

1. Buffer mode: PGA works in unity gain mode.
2. Standalone mode: PGA operates as a conventional op-amp.
3. Non-inverting mode: PGA works as a non-inverting op-amp.
4. Subtractor mode: PGA output voltage equals the subtraction of the inputs applied to inverting and non-inverting pins.

Table 1-1. Modes of Operation

Mode	MUXSEL[PMUXSEL]	MUXSEL[NMUXSEL]	MUXSEL[MMUXSEL]
Buffer mode	0	0	0
Standalone op-amp mode	0	2	0
Non-inverting mode	0	1	1
Subtractor mode	0	1	2 or 3

2 Use Cases

This section reviews the conventional applications of the PGA module. While a traditional op-amp serves as the PGA module's main component, using different settings provides a variety of functionality in the electronic circuit. The code snippets are given to configure miscellaneous settings for each use case, such as the gain and filter resistor selection. The general theory of operational amplifiers is outside the scope of this application note, and many excellent references are given in the reference section.

2.1 Buffer Mode for High-Impedance Source

The input voltage range of the embedded ADC in C2000 real-time microcontroller is limited to 3.3V. This can be sufficient for many applications. However, some applications, such as those using legacy industrial or automotive sensors, can require higher ADC input ranges, such as 5V or 12V. Depending on the application, there can be other design constraints, such as the input source not being able to drive the sampling capacitor of the SAR ADC. Another design concern can be the noise performance of the overall signal chain.

The simplest and lowest-cost method to attenuate a 5V or any other higher voltage signal to 3.3V is through a resistor divider network. Assume that there is an analog sensor that gives a 0-12V range signal. As shown in [Figure 2-1](#), the user can employ a voltage divider with 36k Ω and 100k Ω resistors to bring a 12V sensor voltage down to a level less than 3.3V. However, selecting a Sample+Hold duration that is long enough for this circuit to achieve acceptable settling performance can be difficult. This issue necessitates using a unity-gain op-amp.

To address the issue of driving the SAR ADC from a high impedance source, the buffer mode is implemented in Type-2 PGA. A unity-gain op-amp with low output impedance can drive the resistor divider and provide isolation from the resistor divider and sampling capacitor. Moreover, the buffer mode is beneficial when a sensor has a high output impedance and is directly connected to an ADC for acquisition, then the resulting conversion result can be inaccurate due to the effects of the high impedance signal. Users can also use a filter resistor (100 Ω) and capacitor (1nF) to form a low-pass filter with a cutoff frequency of 1.5MHz.

Note that when the PGA module is configured in a buffer mode, the designated inverting pin of the microcontroller (PGA_INM) is free to be used as general purpose I/O. Also, the Type-1 PGA module does not support the buffer mode.

For more information about driving circuit of the SAR ADC, you can refer to [Charge Sharing Driving Circuits](#), application note which provides an excellent tutorial on how to select a source resistor and charge-sharing capacitor to drive an ADC.

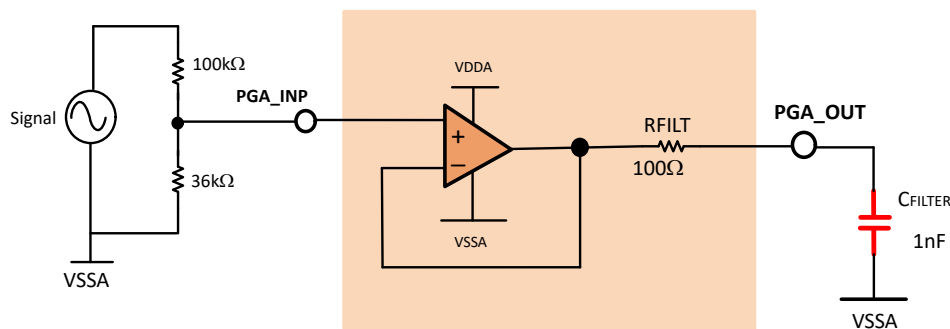


Figure 2-1. Buffer Mode for a High-Impedance Source

The following code snippet shows where to add custom code to set the values for the M, N, and P-MUX to achieve buffer-mode operation, as well as selecting the appropriate filter resistor R_{FILT} connected internally to the output of the PGA module.

```

//
// Filter Resistor
//
#define PGA_FILTERVALUE PGA_LOW_PASS_FILTER_RESISTOR_100_OHM

//
// P-MUX selection
//
#define PGA_PMUXINPUT PGA_PMUX_POS

//
// N-MUX selection
//
#define PGA_NMUXINPUT PGA_NMUX_RTOP

//
// M-MUX selection
//
#define PGA_MMUXINPUT PGA_MMUX_NAKED_OPAMP

```

In the code snippet, PGA_FILTERVALUE represents the desired value for the filter resistor R_{FILT} . Please make sure to consult the documentation or reference manual for your specific device to find the available R_{FILT} values, and then replace PGA_FILTERVALUE with the actual value you want to use in your circuit.

Some applications can not tolerate having an RC network at the output of the amplifier. Amplifier output current flowing through the filter resistor creates a voltage offset that introduces output error. In this case, one can filter the noise spikes by placing a feedback capacitor across the feedback loop. This capacitor can compensate for the zero created by the feedback network and the input capacitance of the PGA module. Indeed, a simple single-pole low-pass filter can be implemented by placing an external capacitance between PGA_INM and PGA_OUT in internal gain mode, demonstrated in Figure 2-2. To enable this filter, set the PGA_FB_ON_PIN register to 1.

The cutoff frequency for this type of filter can be calculated by Equation 1.

$$f_{\text{cutoff}} = \frac{1}{2\pi R_{\text{ib}} C_{\text{Ext}}} \tag{1}$$

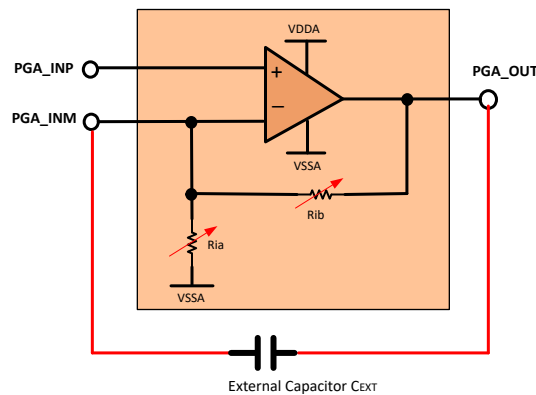


Figure 2-2. Low-Pass Filter Using Embedded Gain Resistor R_{ib} and an External Capacitor

Note

This form of filter is available in the non-inverting and subtractor modes.

2.2 Battery Voltage and Current Monitoring

In portable electronic designs, measuring battery voltage and current is essential to determine when the battery needs to be charged or replaced. The op-amps used in battery-monitoring circuits must meet accuracy requirements while consuming minimal power-supply quiescent current to prolong battery life. This section explains the circuitry for monitoring battery voltage and current in cost-optimized systems using the PGA module. [Figure 2-3](#) illustrates a battery-voltage measurement circuit that utilizes the PGA module configured as a unity-gain buffer. To prevent violations of the amplifier's common-mode input voltage range or output voltage swing, a resistor divider comprised of R_1 and R_2 divides the battery voltage. The output of the circuit can be internally or externally connected to other integrated peripherals within the device.

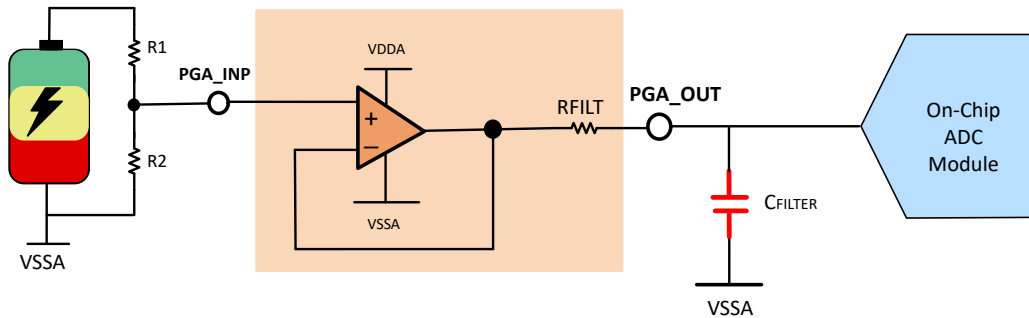


Figure 2-3. Battery-Voltage Measurement Circuit

An understanding of how well a system operates can be gained from the quantity of current flowing through the system. Comparing the current being drawn from a power supply to a pre-defined target range for that specific operating situation provides a fundamental understanding of how efficiently the system operates. Current levels exceeding the expected current level indicate that an element in the system consumes more power than expected. Likewise, if the current is lower than the expected value, this can mean that some part of the system is not powered properly or possibly disconnected.

Measuring the voltage drop across a low-side current-shunt resistor is often the most straightforward approach to determining battery and load current. [Figure 2-4](#) shows an example of the low-side current-sensing circuit using the PGA module. The output of the circuit can be connected to other peripherals, such as the ADC and CMPSS modules, either internally or externally. For example, the CMPSS module can periodically sample the PGA output (with no CPU intervention) and trigger an interrupt when the signal crosses a threshold. The capacitor C_{FB} is connected externally to the output of the PGA module to improve the dynamic performance.

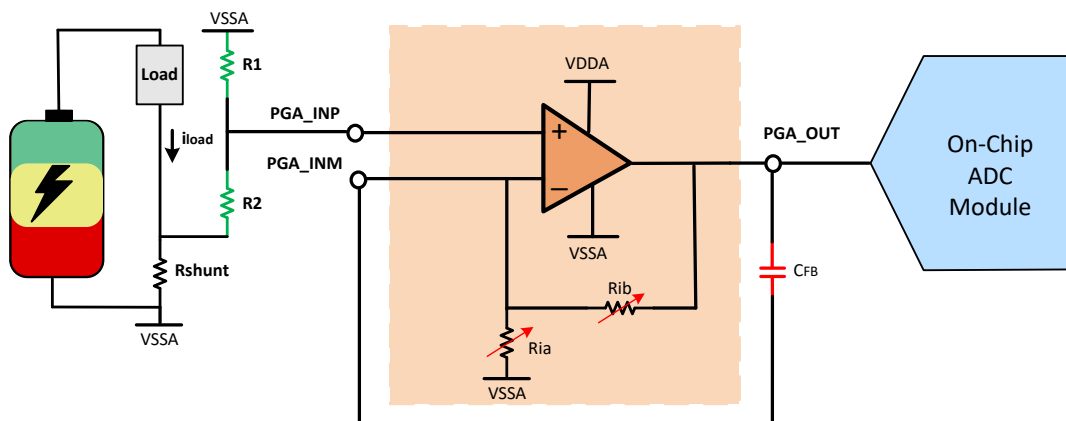


Figure 2-4. Low-Side Battery-Current Measurement Circuit

To customize the gain value and select the appropriate filter resistor for the PGA module, you can refer to the following code snippet. This snippet demonstrates where you can add your own code:

```

//
// Gain
//
#define PGA_GAINVALUE PGA_GAIN_4

//
// Filter Resistor
//
#define PGA_FILTERVALUE PGA_LOW_PASS_FILTER_RESISTOR_100_OHM

//
// P-MUX selection
//
#define PGA_PMUXINPUT PGA_PMUX_POS

//
// N-MUX selection
//
#define PGA_NMUXINPUT PGA_NMUX_RTAP

//
// M-MUX selection
//
#define PGA_MMUXINPUT PGA_MMUX_INVERTING_GAIN_NEG

```

In the code snippet, `PGA_GAINVALUE` represents the desired gain value for the PGA module, and `PGA_FILTERVALUE` represents the desired value for the filter resistor R_{FILT} . Please make sure to consult the documentation or reference manual for your specific device to find the available R_{FILT} and gain values, and then replace `PGA_GAINVALUE` and `PGA_FILTERVALUE` with the actual values you want to use in your circuit.

In some applications, it is undesirable for the voltage potential of the load to be impacted by the voltage drop across the low-side current sensing resistor. To overcome this issue, a high-side battery current-sensing circuit using the on-chip PGA module can be utilized, which is demonstrated in [Figure 2-5](#). This circuit monitors the total current supplied to the load in the positive power supply line. The PGA module measures the differential voltage developed across the sense resistor and sends the output to the CMPSS inverting pin and the ADC module. However, the high-side current measurement is limited to the application with battery voltage of less than V_{DDA} .

For safety purposes, the CMPSS module can periodically sample the PGA output (with no CPU intervention) and trigger an interrupt when the signal crosses a threshold. The output of every CMPSS module can be tied directly into the Trip Zone (TZ) of any ePWM module, and the action when the signal is received is configurable in software. This means there is no software overhead to create the action in the ePWM through software.

If the divider resistors $R_1=R_{\text{ib}}$ and $R_2=R_{\text{ia}}$, the output voltage of the PGA module is given by [Equation 2](#).

$$V_{\text{PGA_OUT}} = \frac{R_{\text{ib}}}{R_{\text{ia}}} \left(R_{\text{shunt}} I_{\text{load}} \right) + V_{\text{REF}} \quad (2)$$

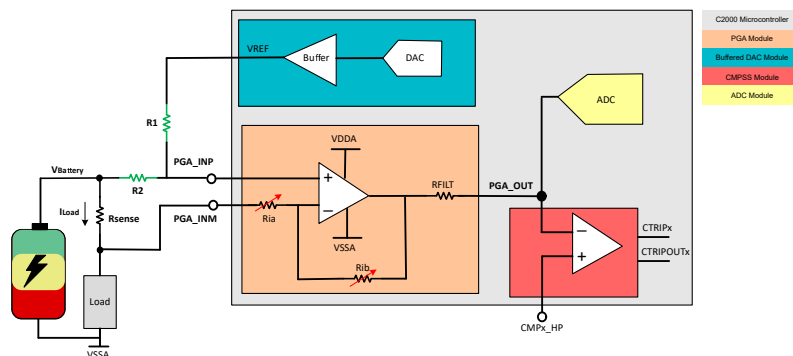


Figure 2-5. High-Side Battery-Current Measurement Circuit

2.3 Low-Side Shunt Current Monitoring

Accurately and quickly detecting load current through a low-side shunt resistor is crucial for various applications such as over-current protection, faster feedback control loops, and battery and power supply monitoring. In low-side current sensing, the sensing resistor is positioned between the load and the ground. The sensing resistor has a low value to prevent obstructing the current flow, resulting in a correspondingly small voltage drop. However, to facilitate upstream conversion by an analog-to-digital converter (ADC), the small voltage across the shunt resistor usually needs to be amplified from tens or hundreds of millivolts to tenths of a volt or even volts. This amplification allows the ADC to measure and process the current information accurately. The PGA module can perform this task.

In [Figure 2-6](#), a scheme of the low-side current sensing in a high-frequency MOSFET leg using a PGA module is depicted. Even though Type-1 PGA supports the low-side current sensing, using Type-2 PGA helps save a pin to use for other functions, such as ADC pin and digital inputs and outputs (AGPIO).

To optimize the current-sensing signal chain, it is crucial to appropriately select the shunt-resistor value and amplifier gain based on the current range and full-scale input range of the ADC. Choosing the right shunt resistor values involves finding the right balance between measurement accuracy and power dissipation across the shunt resistor. If a large-value shunt resistor is used, the resistor can develop a larger differential voltage as current flows through the resistor, resulting in smaller measurement errors due to the fixed amplifier offset voltage. However, a larger signal also creates a larger power dissipation across the shunt resistor, which can pose a challenge to the power dissipation requirement.

Additionally, using smaller shunt resistor values results in a smaller voltage drop across the shunt resistor, which reduces the power dissipation requirements. However, this can also lead to increased measurement errors, as the amplifier's fixed offset errors become a more significant percentage of the signal.

If you want to implement low-pass filtering in your circuit to remove any high-frequency noise, you can combine an external capacitor with the internal filter resistors R_{FILT} . To implement this, you must connect an external capacitor to the output pin of the PGA module. This combination of the external capacitor and internal filter resistors can create a low-pass filter that allows low-frequency signals to pass through while attenuating high-frequency signals.

The same principle applies to selecting amplifier gain, which must be chosen in such a way as to maximize measurement accuracy while minimizing noise.

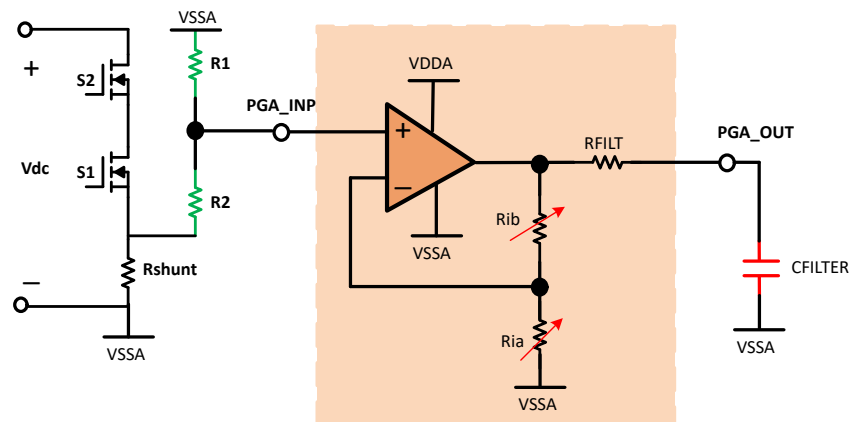


Figure 2-6. Shunt Current Measurement Using a PGA Module

In the circuit shown in [Figure 2-6](#), the amplifier gain is set by the ratio of R_{ib} divided by R_{ia} . If the divider resistors $R_1=R_{ib}$ and $R_2=R_{ia}$, then the amplified voltage can be calculated by [Equation 3](#).

$$V_{PGA_OUT} = \frac{R_{ib}}{R_{ia}} (R_{shunt} I_{load}) \quad (3)$$

The filter cutoff frequency is estimated using [Equation 4](#).

$$f_{cutoff} = \frac{1}{2\pi R_{FILT} C_{FILTER}} \quad (4)$$

If you want to adjust the gain value using the internal gain resistors R_{ia} and R_{ib} , as well as select an appropriate filter resistor R_{FILT} , you can add the following custom code snippet.

```

//
// Gain
//
#define PGA_GAINVALUE PGA_GAIN_4
//
// Filter Resistor
//
#define PGA_FILTERVALUE PGA_LOW_PASS_FILTER_RESISTOR_50_OHM

//
// P-MUX selection
//
#define PGA_PMUXINPUT PGA_PMUX_POS

//
// N-MUX selection
//
#define PGA_NMUXINPUT PGA_NMUX_RTAP

//
// M-MUX selection
//
#define PGA_MMUXINPUT PGA_MMUX_NON_INVERTING_GAIN_VSSA
  
```

In the code snippet, `PGA_GAINVALUE` represents the desired gain value for the PGA module, and `PGA_FILTERVALUE` represents the desired value for the filter resistor R_{FILT} . Please make sure to consult the documentation or reference manual for your specific device to find the available R_{FILT} and gain values, and then replace `PGA_GAINVALUE` and `PGA_FILTERVALUE` with the actual values you want to use in your circuit.

2.4 Three-Phase Low-Side Current Sensing

In applications requiring multiple PGAs, the PGA modules enables the sharing of a common negative sense point (PGA_INM), which leads to less pin usage. This feature is feasible because the PGA_INM pin in the PGA3 module is internally connected to VSSA. To enable this feature, PMUX_SEL must be set to 3. For instance, three PGA modules can be utilized for current measurement in a three-phase inverter with only four pins.

The implementation of three-phase current sensing is shown in Figure 2-7. Even though Type-1 PGA supports there-phase low-side current sensing, using Type-2 PGA helps save two pins for other functionality, such as ADC pin and digital inputs and outputs (AGPIO).

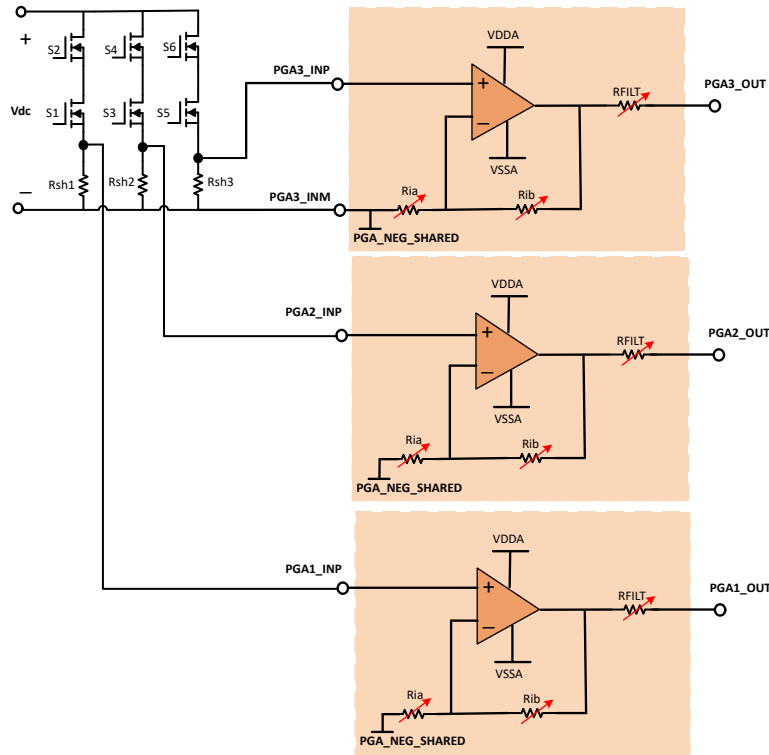


Figure 2-7. Three-Phase Current Sensing Using the PGA_NEG_SHARED Feature

2.5 Bidirectional Current Sensing

Bidirectional current sensing is needed in many battery-current monitoring applications to measure the battery's charge and discharge currents. To enable bidirectional current sensing, a positive voltage is applied to the non-inverting pin to offset the output voltage. If the differential input voltage is positive, the output voltage can be greater than the applied reference voltage; conversely, if the differential input voltage is negative, the output voltage can be lower than the applied reference voltage. As shown in Figure 2-8, the PGA module, in combination with DAC and ADC modules, senses the current flow through a sense resistor in both directions. An embedded buffered DAC module provides the reference voltage V_{REF} . If the divider resistors $R_1=R_{ib}$ and $R_2=R_{ia}$, the output voltage of the PGA is given by Equation 5.

$$V_{PGA_OUT} = \frac{R_{ib}}{R_{ia}} \left(R_{shunt} I_{load} \right) + V_{REF} \quad (5)$$

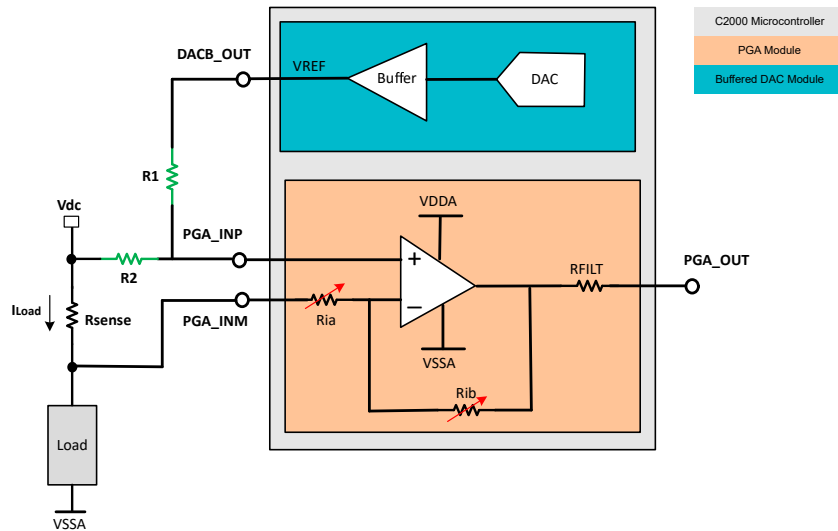


Figure 2-8. Bidirectional Current Sensing

2.6 Non-Inverting Amplifier for Low-Voltage Sensors

Given a small positive signal, the PGA can amplify the signal to increase the dynamic range of ADC sampling and comparator trip monitoring. For example, as shown in Figure 2-9, the PGA module configured in 4x mode amplifies an input signal with a valid range between 0.25V and 0.75V to produce an output signal between 1V and 3V. Please note that no PGA_INM pin connection is needed in this application while using the internal connection to VSSA. Even though the non-inverting mode is supported in Type-1 PGA, using Type-2 PGA helps save a pin to use for other functionalities, such as ADC pin and digital inputs and outputs (AGPIO).

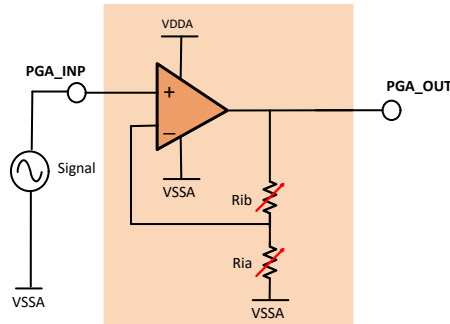


Figure 2-9. Non-Inverting Amplifier Implementation Using a PGA Module

The amplified output voltage is calculated as follows.

$$V_{PGA_OUT} = \left(1 + \frac{R_{ib}}{R_{ia}}\right) V_{Signal} \quad (6)$$

The following code snippet shows where to add custom code to adjust the gain value using the internal gain resistors R_{ia} and R_{ib} , as well as selecting the appropriate filter resistor R_{FILT} connected internally to the output of the PGA module.

```

//
// Gain
//
#define PGA_GAINVALUE PGA_GAIN_4

//
// Filter Resistor
//
#define PGA_FILTERVALUE PGA_LOW_PASS_FILTER_RESISTOR_50_OHM

//
// P-MUX selection
//
#define PGA_PMUXINPUT PGA_PMUX_POS

//
// N-MUX selection
//
#define PGA_NMUXINPUT PGA_NMUX_RTAP

//
// M-MUX selection
//
#define PGA_MMUXINPUT PGA_MMUX_NON_INVERTING_GAIN_VSSA

```

In the code snippet, `PGA_GAINVALUE` represents the desired gain value for the PGA module, and `PGA_FILTERVALUE` represents the desired value for the filter resistor R_{FILT} . Please make sure to consult the documentation or reference manual for your specific device to find the available R_{FILT} and gain values, and then replace `PGA_GAINVALUE` and `PGA_FILTERVALUE` with the actual values you want to use in your circuit.

2.7 Non-Inverting Amplifier for Bipolar Signals

To sample a bipolar signal and translate the sample to a range designed for downstream ADC and CMPSS modules, a combination of the PGA and DAC modules can be employed. Another use case for this mode is a Hall effect sensor that senses the total current flowing in a circuit. The Hall effect sensor has an inbuilt offset, and the range is different than what ADC can measure. Hence, a voltage conditioning circuit is needed. As an example, while the PGA works in non-inverting mode, the PGA can help to translate an input signal of $-1V$ to $2V$ to an output voltage of $0.05V$ to $3.3V$. The signal conditioning circuit is shown in [Figure 2-10](#). The reference voltage can be generated using an embedded buffered DAC. Even though Type-1 PGA supports the non-inverting mode, using Type-2 PGA helps save a pin to use for other functions, such as ADC pin and digital inputs and outputs (AGPIO).

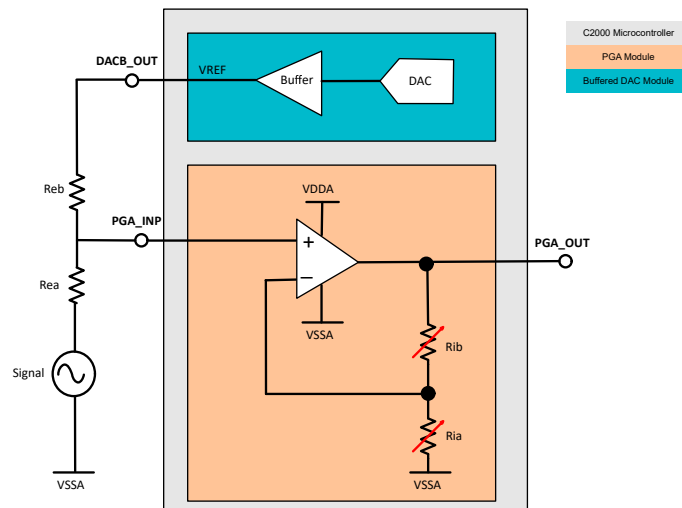


Figure 2-10. Signal Conditioning for a Bipolar Signal Using Non-inverting Mode

Assuming that the divider resistors $R_{ea}=R_{ia}$ and $R_{eb}=R_{ib}$, the relationship between the output voltage V_{PGA_OUT} , reference voltage V_{REF} , and input signal V_{signal} is given by Equation 7.

$$V_{PGA_OUT} = \left(1 + \frac{R_{ib}}{R_{ia}} \right) V_{Signal} + V_{REF} \quad (7)$$

The equation implies that the circuit can be used to translate a negative sensor output voltage to a usable ADC input voltage range, in which PGA is employed in non-inverting mode.

The following code snippet shows where to add custom code to adjust the gain value using the internal gain resistors R_{ia} and R_{ib} , as well as selecting the appropriate filter resistor R_{FILT} connected internally to the output of the PGA module.

```
//
// Gain
//
#define PGA_GAINVALUE PGA_GAIN_4

//
// Filter Resistor
//
#define PGA_FILTERVALUE PGA_LOW_PASS_FILTER_RESISTOR_800_OHM

//
// P-MUX selection
//
#define PGA_PMUXINPUT PGA_PMUX_POS

//
// N-MUX selection
//
#define PGA_NMUXINPUT PGA_NMUX_RTAP

//
// M-MUX selection
//
#define PGA_MMUXINPUT PGA_MMUX_INVERTING_GAIN_NEG
```

In the code snippet, `PGA_GAINVALUE` represents the desired gain value for the PGA module, and `PGA_FILTERVALUE` represents the desired value for the filter resistor R_{FILT} . Please make sure to consult the documentation or reference manual for your specific device to find the available R_{FILT} and gain values, and then replace `PGA_GAINVALUE` and `PGA_FILTERVALUE` with the actual values you want to use in your circuit.

2.8 Standalone Mode for Various Applications

The PGA modules are designed to be used as standalone operational amplifiers to provide a well-integrated, cost-effective signal conditioning system designed for various applications. This mode gives the designers the flexibility to configure the PGA module with customized gain value. Other analog peripherals, such as DAC and CMPSS modules, can be used in conjunction with the PGA to unlock new uses for existing peripherals. The circuit diagram of PGA in this mode is shown in Figure 2-11.

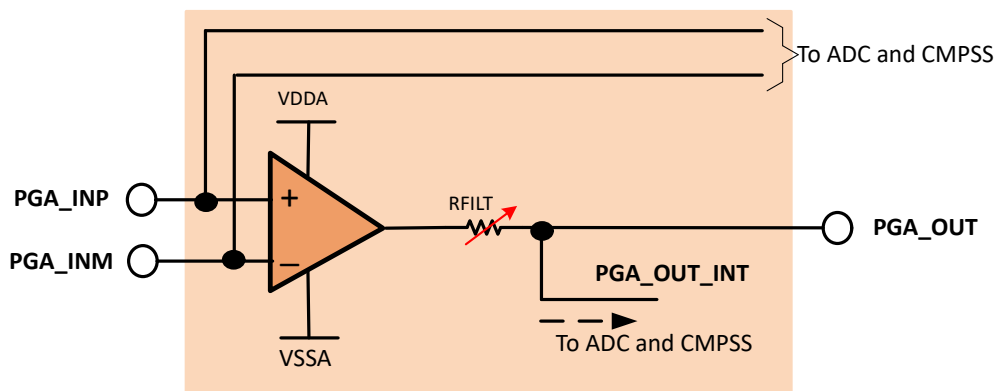


Figure 2-11. Circuit Diagram of Standalone Mode

The following code snippet shows the code to configure the PGA module in standalone mode.

```
//  
// P-MUX selection  
//  
#define PGA_PMUXINPUT    PGA_PMUX_POS  
  
//  
// N-MUX selection  
//  
#define PGA_NMUXINPUT    PGA_NMUX_NEG  
  
//  
// M-MUX selection  
//  
#define PGA_MMUXINPUT    PGA_MMUX_NAKED_OPAMP
```

3 Summary

The programmable gain amplifier (PGA) is a high-performance analog front-end that is designed for various applications, such as sensor signal acquisition and DC supply current sensing. The PGA is an operational amplifier-based module with multiple internal programmable gains and filter resistors. With the help of the PGA on all devices with a Type-2 PGA module, the low-voltage on-chip or off-chip ADCs can process a wide range of input signals. Gain flexibility and embedded low-pass filtering enable the current or voltage waveform to be boosted without adding additional gain stages or degrading performance and simplify the design process.

4 References

- Texas Instruments, [C2000 Real-Time Control MCU Peripherals](#) reference guide.
- Texas Instruments, [Charge Sharing Driving Circuits](#), application note.
- Texas Instruments, [Analog Engineer's Circuit Cookbook: Amplifiers](#).
- Texas Instruments, [Simplifying Current Sensing](#).
- Texas Instruments, [An Applications Guide for Op Amps](#), application note.

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