**Programmable-gain amp achieves high gains**


Most data acquisition systems with a wide dynamic range need some method of adjusting the input signal level to the analog-to-digital converter (ADC) to maximize use of the ADC’s full-scale input voltage range. To achieve this, a programmable-gain amplifier (PGA) or a variable-gain amplifier (VGA) is usually located between a sensor and its ADC, as shown in Figure 1. Additional signal conditioning may take place before or after the PGA or VGA, depending on the application.

![Figure 1](image1)

**Figure 1** PGA in data acquisition system

When high gains are needed, the topology of the PGA circuit deserves extra thought. It is not advisable to use feedback resistors with a very high value (>1MO) due to noise and op-amp offset current. In addition, for an inverting amp, high gain can result in low input resistance.

This Design Idea presents a PGA circuit which satisfies these conditions. Figure 2 shows the two versions, having eight digitally programmable gains.

![Figure 2a](image2)

**Figure 2a** Inverting PGA circuit
Although the number of gains that can be implemented with these circuits is equal to $2^n$, where $n$ is the number of used MOSFETs, it is only possible to implement $n+1$ independent gains.

Signals $D_1$, $D_2$, and $D_3$ select the gain of the amplifier. The switches will typically be “logic level” MOSFETs with $R_{DSon}$ as low as possible (e.g., 2N7002P with $R_{DSon\,(typ)} = 1\Omega$ or IRLML2502 with a $R_{DSon\,(typ)} = 0.05\Omega$).

The independent gains that can be selected in the amplifier circuit shown in Figure 2a are:

\[
\begin{align*}
D_3 D_2 D_1 &= 0 0 0 \rightarrow \quad G_0 &= \frac{v_o}{v_i} = -\frac{1}{R_1} \left[ R_2 + R_3 \right] \\
D_3 D_2 D_1 &= 0 0 1 \rightarrow \quad G_1 &= \frac{v_o}{v_i} = -\frac{1}{R_1} \left[ R_2 + R_3 + \frac{R_2 R_3}{R_{a1}} \right] \\
D_3 D_2 D_1 &= 0 1 0 \rightarrow \quad G_2 &= \frac{v_o}{v_i} = -\frac{1}{R_1} \left[ R_2 + R_3 + \frac{R_2 R_3}{R_{a2}} \right] \\
D_3 D_2 D_1 &= 1 0 0 \rightarrow \quad G_3 &= \frac{v_o}{v_i} = -\frac{1}{R_1} \left[ R_2 + R_3 + \frac{R_2 R_3}{R_{a3}} \right]
\end{align*}
\]
Restrictions

For **Figure 2a**, when two or more MOSFETs are used, the MOSFET body diodes will start to conduct if the input voltage \(v_i\) takes too large a value, distorting the output voltage of the amplifier. To avoid this, the following condition must be satisfied:

\[
v_i \leq \frac{R_1}{R_2} \cdot v_F
\]

where \(v_F\) is the **body diode forward voltage of the MOSFET** \((v_F > 0)\).

When only one MOSFET is used, the input voltage must fulfill the following condition to avoid body diode conduction:

\[
v_i \leq \frac{R_1}{R_2} \left(1 + \frac{R_{D_S_{on}}}{R_{DS_{on}}} \right) \cdot v_F
\]

The independent gains that can be selected in the amplifier circuit shown in **Figure 2b** are:

\[
D_3 \: D_2 \: D_1 = 0 \: 0 \: 0 \rightarrow G_0 = \frac{v_0}{v_i} = \frac{R_1 + R_2 + R_3}{R_1}
\]

\[
D_3 \: D_2 \: D_1 = 0 \: 0 \: 1 \rightarrow G_1 = \frac{v_0}{v_i} = \frac{R_3}{R_1} \left(1 + \frac{R_1 + R_2}{R_3 PR_{al1}} \right)
\]

\[
D_3 \: D_2 \: D_1 = 0 \: 1 \: 0 \rightarrow G_2 = \frac{v_0}{v_i} = \frac{R_3}{R_1} \left(1 + \frac{R_1 + R_2}{R_3 PR_{al2}} \right)
\]

\[
D_3 \: D_2 \: D_1 = 1 \: 0 \: 0 \rightarrow G_3 = \frac{v_0}{v_i} = \frac{R_3}{R_1} \left(1 + \frac{R_1 + R_2}{R_3 PR_{al3}} \right)
\]

For **Figure 2b**, when using two or more MOSFETs, the body diodes will conduct if the input voltage \(v_i\) takes too large a negative value. To avoid this, the following condition must be satisfied:

\[
v_i \geq \frac{-v_F}{1 + R_2/R_1}
\]

When only one MOSFET is used, the input voltage must fulfill the following condition to avoid body diode conduction:

\[
v_i \geq \left(\frac{1 + R_{D_S_{on}}/R_{DS_{on}}}{1 + R_2/R_1}\right) \cdot v_F
\]
**Figure 3** shows a practical application of the circuit of **Figure 2a**. In this example, a PGA is used to amplify the output voltage ($v_i$) of a circuit that integrates and filters the signal generated by a Rogowski coil.

![Image](image.jpg)

**Figure 3** AC measurement system based on a Rogowski coil

It has been assumed that the ADC that will sample the signal $v_o = k \cdot i(t)$ has reference voltages of $v_{ref^+} = 2.5\text{v}$ and $v_{ref^-} = -2.5\text{v}$, the Rogowski coil has a sensitivity of 30µV/A, the integrator/high-pass filter has a gain equal to $1.2 = 1.64 \text{ dBs}$ at 50Hz, and we want to measure AC currents in the following ranges: $1280\text{A}_\text{rms}$, $320\text{A}_\text{rms}$, $80\text{A}_\text{rms}$ and $20\text{A}_\text{rms}$. According to the previous data, the gains that we should be able to select are: $G_0 = -38.363$, $G_1 = -153.452$, $G_2 = -613.808$, and $G_3 = -2455.2$. A simple method to calculate the resistor values is:

- $R_{a3} = 300 \cdot R_{DS-on} = 300 \cdot 10 = 3000 \Omega$ we set the smallest value of the $R_a$ resistors to ensure that the value of $R_{DS-on}$ does not have a significant influence on the amplifier gains.

$$R_2 = R_3 = 2 \cdot R_{a3} \cdot (G_3 - G_0)/G_0 = 37799.9 \approx 38000 \Omega$$

$$R_1 = -4 \cdot R_{a3} \cdot (-1 + G_3/G_0)/G_0 = 1970.6 \approx 1970 \Omega$$

$$R_{a1} = R_{a3} \cdot (G_3 - G_0)/(G_1 - G_0) = 6299.8 \approx 6300 \Omega$$

$$R_{a2} = R_{a3} \cdot (G_3 - G_0)/(G_2 - G_0) = 1260 \Omega$$

The gains obtained with the calculated values are (theoretical values are shown in square brackets):

$$D_3 \ D_2 \ D_1 = 0 \ 0 \ 0 \ \ ? \ \ G_0 = -38.3756 \ [-38.363]$$
For a non-inverting design, the following method can be used to select resistor values that provide gains $G_0 = 38.363$, $G_1 = 153.452$, $G_2 = 613.808$, and $G_3 = 2455.2$:

\[
R_{a3} = 300 \cdot R_{D^S\text{-on}} = 300 \cdot 1\Omega = 300\ \Omega
\]
\[
R_2 = 2 \cdot R_{a3} \cdot (G_3 - G_0)/(1 + G_0) = 36840\ \Omega
\]
\[
R_3 = R_2
\]
\[
R_1 = 4 \cdot R_{a3} \cdot (G_3 - G_0)/( -1 + G_0^2) = 1972\ \Omega
\]
\[
R_{a1} = R_{a3} \cdot (G_3 - G_0)/( G_1 - G_0) = 6300\ \Omega
\]
\[
R_{a2} = R_{a3} \cdot (G_3 - G_0)/( G_2 - G_0) = 1260\ \Omega
\]

The gains obtained with the calculated values are:

\[
D_3 D_2 D_1 = 0 0 0\ ?\ G_0 = 38.3631\ [38.363]
\]
\[
D_3 D_2 D_1 = 0 0 1\ ?\ G_1 = 153.4532\ [153.452]
\]
\[
D_3 D_2 D_1 = 0 1 0\ ?\ G_2 = 613.8139\ [613.808]
\]
\[
D_3 D_2 D_1 = 1 0 0\ ?\ G_3 = 2455.3\ [2455.2]
\]

Also see:

- Low-noise ac amplifier has digital control of gain and bandwidth