KWIK CIRCUIT FAQ

Bipolar Input to Unipolar Output Signal Conditioning

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FAQ: Bipolar Input to Unipolar Output Signal Conditioning

Introduction

Inputs to ADCs are typically unipolar signals which swing from ground to the positive full-scale. Bipolar signals, which swing to positive and negative, require a circuit driver that translates and compresses the bipolar signals to the unipolar range of the ADC's input (refer to Figure 1).

A typical op-amp ADC driver scaling circuit needs a reference voltage, resistors for dividers, and an op-amp supply voltage.

This KWIK (Know-how With Integrated Knowledge) Circuit application note offers a step by step guide to address a specific design challenge. For a given set of application circuit requirements, it illustrates how these are addressed using generic formulae and makes them easily scalable to other similar application specifications.

This KWIK note provides a general procedure for scaling and level shifting for a given value of biasing voltage, V_{ref}. Utilizing scaling resistors, a step-by-step guide in computing the resistor and capacitor values is provided. A sample design problem is solved in this application note with the specifications in Table 1.

Design Specifications Example

For this example, the design requirement specifications are shown in Table 1. Input is -5V to 5V, as seen in Figure 1. Desired output is a unipolar signal from 0.1V to 4.9V. For a low offset voltage op-amp, $V_{out} \approx V_c$.

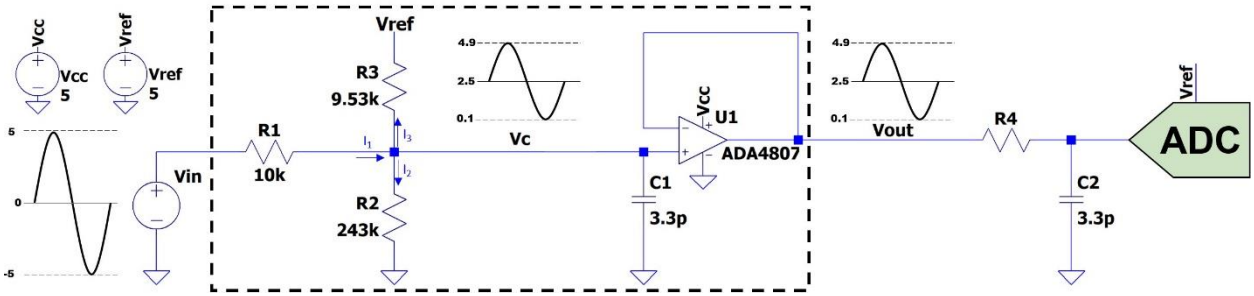

Figure 1. – Bipolar to Unipolar Conversion with Scaling and Level Shifting

Table 1. Design Specifications

Input (Vin)		Output (Vo)		Supply		
VinMin	VinMax	VoutMin = VcMin	VoutMax = VcMax	VCC	VEE	Vref
-5V	5V	0.1V	4.9V	5V	0V	5V

Design Description

Scaling and level shifting is possible using 2 resistors. However, V_{ref} would need to be a non-standard value (i.e. 5.48V or 3.38V). To eliminate the need of a non-standard V_{ref}, 3 resistors are used to scale V_{in} to V_c by setting the gain and offset.

Using superposition, ground V_{in} and V_{ref} one at a time. Grounding V_{ref} creates a resistor voltage divider circuit that scales the AC input, V_{in}. Refer to Figure 2. Using nodal analysis gives Equation 1.

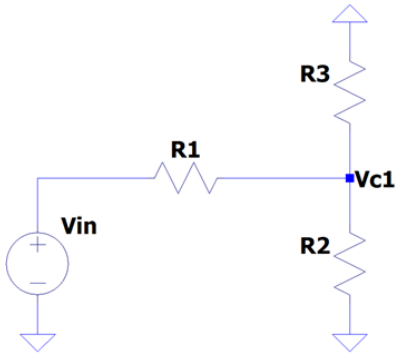

Figure 2. – Grounded V_{ref}

$$V_{c1} = \frac{R_2 \parallel R_3}{R_1 + (R_2 \parallel R_3)}(V_{in}) \qquad \text{(Eq. 1)}$$

In Figure 3, Vin is grounded and biasing voltage, V_{ref}, is connected. This circuit utilizes the same resistors to set appropriate DC offset to level shift the scaled signal. Using nodal analysis gives Equation 2.

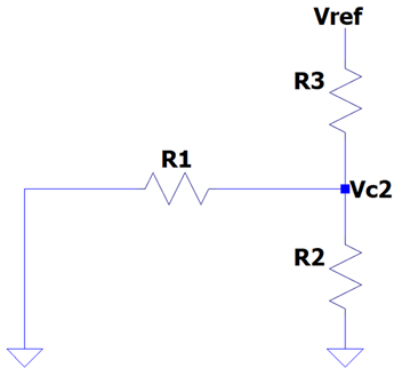

Figure 3. – Grounded V_{in}

$$V_{c2} = \frac{R_1 \parallel R_2}{R_3 + (R_1 \parallel R_2)}(V_{ref}) \qquad \text{(Eq. 2)}$$

Adding equations 1 and 2 gives the general equation of the scaled and level shifted signal, V_c, in terms of V_{in} and V_{ref}.

$$V_c = \frac{R_2 \parallel R_3}{R_1 + (R_2 \parallel R_3)}(V_{in}) + \frac{R_1 \parallel R_2}{R_3 + (R_1 \parallel R_2)}(V_{ref})$$

(Eq. 3)

In this sample design, the circuit is expected to drive ADCs used in machine automation and medical equipment applications with V_{ref} = 5V, with sample rates of 2MSPS to 10MSPS. The AD4000 can operate up to 2 MSPS. ADA4807, one of the recommended drivers of AD4000, is used as the driver in the design sample.

Design Tips / Considerations

1. Ensure the op-amp Input Voltage Range (common mode input voltage) is observed.
2. Use the op-amp Open-Loop Voltage Gain test conditions to establish linear output range. (i.e. ADA4807: V_S=5V, R_L=1kΩ to midsupply, 0V ≤ V_{ICM} ≤ +V_S-1.5V)
3. Do not use the op-amp Saturated Output Voltage Swing for linear operation. (i.e. ADA4807: V_S=5V, R_L=1kΩ , V_{out}=0.05V to +4.95V)
4. Use available voltage source in the circuit/system, such as V_{ref}, as biasing voltage while considering its current drive capability.
5. Use low tolerance resistors for the voltage divider to minimize gain error.
6. Use a higher supply voltage for the op-amp than ADC's positive full-scale to account for the amplifier's output headroom or use a rail-to-rail output op-amp.

Design Procedure

In the design procedure, nodal analysis is used to get the resistor values. The same resistor values should be obtained using superposition as validated at the end of this section.

1. Variable Definition

The linear op amp circuit transfer function can be modelled as a straight-line equation.

$$y = mx + b$$

Where: m = slope or scaling coefficient

b = offset or level translator

y = V_{OUT}

x = V_{IN}

From the design key specification, there is a max and min case. Use this to mathematically define m and b.

$$m = \frac{V_{cMax} - V_{cMin}}{V_{inMax} - V_{inMin}}$$

$$b = V_{cMax} - V_{inMax} * m$$

2. Resistance Computation

1. Obtain the working equation using nodal analysis at node V_c. Refer to Figure 1. Current entering node V_c, I_1, is equal to currents leaving, I_2 and I_3.

$$I_1 = I_2 + I_3$$

$$\frac{V_{in} - V_c}{R_1} = \frac{V_c}{R_2} + \frac{V_c - V_{ref}}{R_3} \quad \text{(Eq. 4)}$$

2. Below is the simplified equation for R_3 and R_2, using Eq. 4 and the max and min cases. For the complete derivation, see the Appendix.

$$R_3 = \frac{(m)(V_{ref})(R_1)}{b}$$

$$R_2 = \frac{mR_1R_3}{R_3 - m(R_3 + R_1)}$$

3. Compute value of m and b. Use the linear output range of ADA4807, 0.1V to 4.9V.

   Note: The linear output voltage range of V_c is within the input common mode of the op-amp, ADA4807(V_{SY}=5V, V_{CMmin}=-0.2V, V_{CMmax}=5.2V).

$$m = \frac{V_{cMax} - V_{cMin}}{V_{inMax} - V_{inMin}} = \frac{4.9V - 0.1V}{5V - (-5V)} = 0.48$$

$$b = V_{cMax} - V_{inMax} * m = 4.9V - 5V(0.48) = 2.5V$$

4. Solve for R_3 and R_2. To only have two unknowns and two equations, set value of R_1. In this example, R_1=10kΩ. The higher the resistor values, the less power needed, at the trade-off of higher noise.

$$R_3 = \frac{(m)(V_{ref})(R_1)}{b} = \frac{(0.48)(5V)(10k\Omega)}{2.5V}$$

$$R_3 = 9600\Omega \rightarrow \text{ std. value } 9.53k\Omega$$

$$R_2 = \frac{mR_1R_3}{R_3 - m(R_3 + R_1)} = \frac{(0.48)(10k\Omega)(9600\Omega)}{9600\Omega - (0.48)(9600\Omega + 10k\Omega)}$$

$$R_2 = 240k\Omega \rightarrow \text{ std. value } 243k\Omega$$

5. For noise reduction, a capacitor may be added in the input of the op-amp. Use the cutoff frequency equation to compute the capacitor value. Set cutoff frequency at least 1 decade away from target operating frequency. Lower capacitance gives higher bandwidth. Set cutoff frequency to 10 MHz; two decades away from the frequency used in the simulation.

$$F_{cutoff} = \frac{1}{2\pi(R_{equivalent})(C_1)}$$

$$C_1 = \frac{1}{2\pi(F_{cutoff})(R_{equivalent})}$$

Where: $R_{equivalent} = R_1 \,||\, R_2 \,||\, R_3$

$$C_1 = \frac{1}{2\pi(10MHz)\left(\frac{1}{\frac{1}{10k\Omega} + \frac{1}{9600\Omega} + \frac{1}{240k\Omega}}\right)}$$

$$C_1 = 3.32\,pF \rightarrow \text{ std. value } 3.3\,pF$$

3. Superposition Equation Validation

Equation below is the transfer function of the design circuit. Substitute resistor values to the general equation from the design description. From the computations above, R_1=10kΩ, R_2=240kΩ, and R_3=9.6kΩ

$$V_c = V_{out} = \frac{R_2 \parallel R_3}{R_1 + (R_2 \parallel R_3)}(V_{in}) + \frac{R_1 \parallel R_2}{R_3 + (R_1 \parallel R_2)}(V_{ref})$$

$$ScalingCoefficient = \frac{R_2 \parallel R_3}{R_1 + (R_2 \parallel R_3)} = \frac{\left(\frac{R_2 * R_3}{R_2 + R_3}\right)}{R_1 + \left(\frac{R_2 * R_3}{R_2 + R_3}\right)}$$

$$\frac{\left(\frac{240k\Omega * 9.6k\Omega}{240k\Omega + 9.6k\Omega}\right)}{10k\Omega + \left(\frac{240k\Omega * 9.6k\Omega}{240k\Omega + 9.6k\Omega}\right)} = 0.48 = m$$

$$LevelShift = \frac{R_1 \parallel R_2}{R_3 + (R_1 \parallel R_2)}(V_{ref}) = \frac{\left(\frac{R_1 * R_2}{R_1 + R_2}\right)}{R_3 + \left(\frac{R_1 * R_2}{R_1 + R_2}\right)}(V_{ref})$$

$$\frac{\left(\frac{10k\Omega * 240k\Omega}{10k\Omega + 240k\Omega}\right)}{9.6k\Omega + \left(\frac{10k\Omega * 240k\Omega}{10k\Omega + 240k\Omega}\right)}(5V) = 2.5V = b$$

$$V_{out} = m(V_{in}) + b$$

$$V_{out} = 0.48(V_{in}) + 2.5V \quad \text{(Eq. 5)}$$

$$V_{outMax} = m(V_{inMax}) + b$$

$$V_{outMax} = 0.48(5V) + 2.5V = 4.9V$$

$$V_{outMin} = m(V_{inMin}) + b$$

$$V_{outMin} = 0.48(-5V) + 2.5V = 0.1V$$

Correct V_{in} to V_{out} mapping is verified from Equation 5 by substituting V_{inMax}=5V and V_{inMin}=-5V.

Design Simulations

The circuit shown in Figure 1 was simulated using the LTSpice simulation tool to determine if the 0.1V – 4.9V output range was met. Figure 4 shows the input signal, V_{in}, versus the conditioned signal, V_C. Note: Simulation used standard value resistors, R_1=10kΩ, R_2=243kΩ, R_3=9.53kΩ and C_1=3.3pF.

Use of a rail-to-rail input and output (RRIO) op-amp in its linear output voltage swing range and with its low input offset voltage, adds minimal error from VC to V_{out}. The simulation presented in Figure 4 used the ADA4807. There is minimal difference between V_c, 4.7824V_{pp} (0.1243V–4.9067V), and V_{out}, 4.7825V_{pp} (0.1241V–4.9066V).

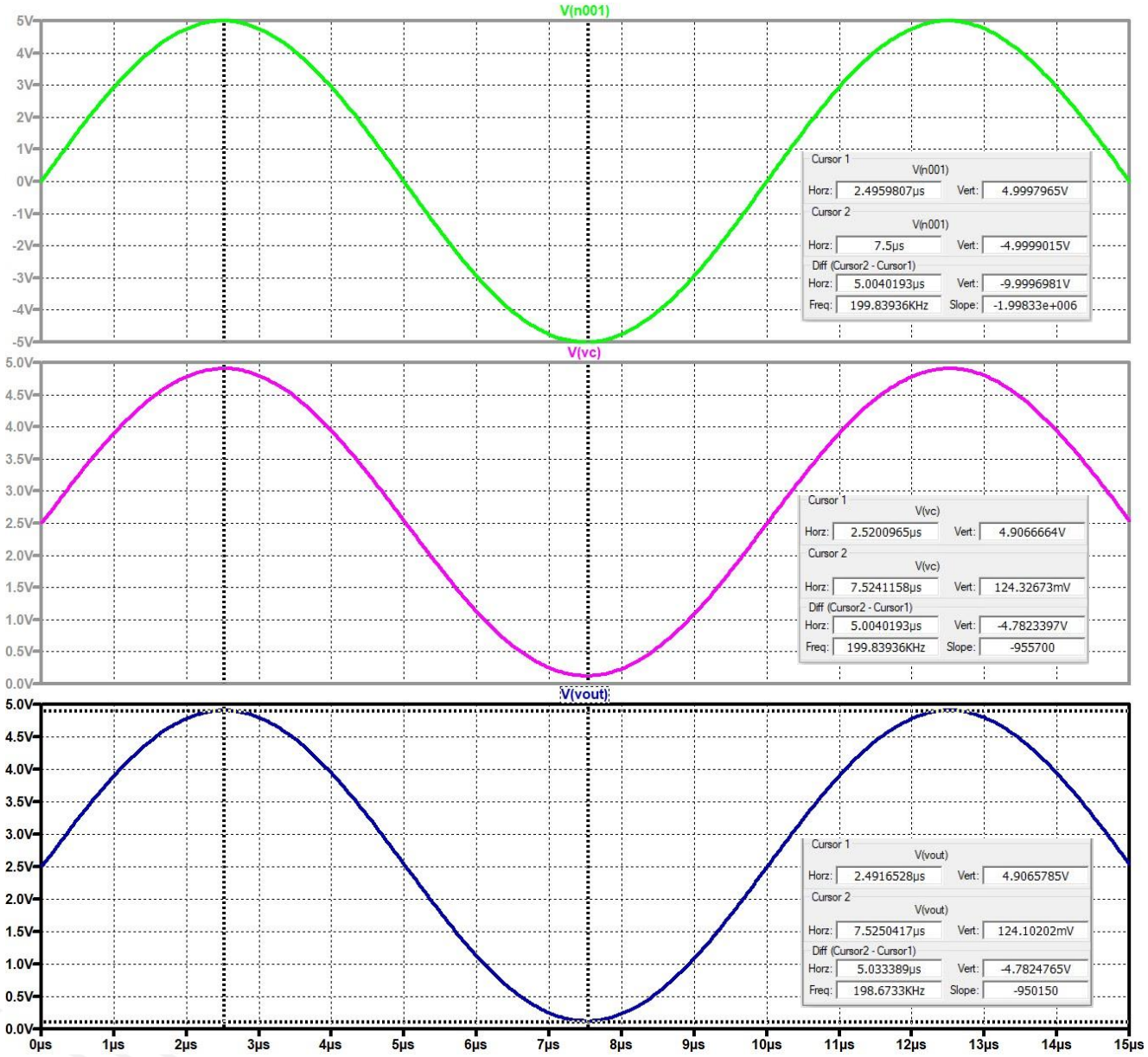

Figure 4. – Input vs Conditioned vs Output

Design Devices

Table 2. Op Amp

Part Number	Input Voltage Range (V)	Gain Bandwidth Product (Hz)	Slew Rate (V/µs)
ADA4807	$-V_S$-0.2 to $+V_S$+0.2	28M	145/160

References

Analog Devices publishes circuit notes for reference designs that provides computation, design consideration and bench measurements. Below are some of the mini tutorials and circuit notes that have been proven useful in writing this application note.

MT-041: Op Amp Input and Output Common-Mode and Differential Voltage Range
MT-064: In-Amp DC Error Sources
CN-0314 - Configurable 4-20 mA Loop Powered Transmitter/Receiver using a Micropower Instrumentation Amplifier

LTspice

LTspice® is a high-performance SPICE III simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulator, linear, and signal chain circuits

Appendix

Step by step derivation of R3 and R2 equation.

$$\frac{V_{in}-V_c}{R_1}=\frac{V_c}{R_2}+\frac{V_c-V_{ref}}{R_3}$$

$$m=\frac{V_{cMax}-V_{cMin}}{V_{inMax}-V_{inMin}}$$

$$b=V_{cM\,ax}-V_{inMax}*m$$

Min case:

$$\frac{V_{inMin}-V_{cMin}}{R_1}=\frac{V_{cMin}}{R_2}+\frac{V_{cMin}-V_{ref}}{R_3}$$

Max case:

$$\frac{V_{inMax}-V_{cMax}}{R_1}=\frac{V_{cMax}}{R_2}+\frac{V_{cMax}-V_{ref}}{R_3}$$

1. EQUATION FOR R3 DERIVATION

Using the equations from min and max case, solve for R3.

Equation X:

$$\left(\frac{V_{inMin}-V_{cMin}}{R_1}=\frac{V_{cMin}}{R_2}+\frac{V_{cMin}-V_{ref}}{R_3}\right)\left(V_{cMax}\right)\rightarrow\frac{\left(V_{cMax}\right)\left(V_{inMin}-V_{cMin}\right)}{R_1}=\frac{V_{cMin}V_{cMax}}{R_2}+\frac{\left(V_{cMax}\right)\left(V_{cMin}-V_{ref}\right)}{R_3}$$

Equation Y:

$$\left(\frac{V_{inMax}-V_{cMax}}{R_1}=\frac{V_{cMax}}{R_2}+\frac{V_{cMax}-V_{ref}}{R_3}\right)\left(-V_{cMin}\right)\rightarrow\frac{\left(-V_{cMin}\right)\left(V_{inMax}-V_{cMax}\right)}{R_1}=\frac{-V_{cMin}V_{cMax}}{R_2}+\frac{\left(-V_{cMin}\right)\left(V_{cMax}-V_{ref}\right)}{R_3}$$

To eliminate the other variable, R2, add equation X and equation Y.

$$\frac{\left(V_{cMax}\right)\left(V_{inMin}-V_{cMin}\right)}{R_1}=\frac{V_{cMin}V_{cMax}}{R_2}+\frac{\left(V_{cMax}\right)\left(V_{cMin}-V_{ref}\right)}{R_3}$$

$$\frac{(-V_{cMin})(V_{inMax}-V_{cMax})}{R_1}=\frac{-V_{cMin}V_{cMax}}{R_2}+\frac{(-V_{cMin})(V_{cMax}-V_{ref})}{R_3}$$

$$\left(\frac{(V_{cMax})(V_{inMin}-V_{cMin})}{R_1}\right)+\left(\frac{(-V_{cMin})(V_{inMax}-V_{cMax})}{R_1}\right)=\left(\frac{V_{cMin}V_{cMax}}{R_2}+\frac{(V_{cMax})(V_{cMin}-V_{ref})}{R_3}\right)+\left(\frac{-V_{cMin}V_{cMax}}{R_2}+\frac{(-V_{cMin})(V_{cMax}-V_{ref})}{R_3}\right)$$

$$\frac{V_{cMax}(V_{inMin}-V_{cMin})-V_{cMin}(V_{inMax}-V_{cMax})}{R_1}=\frac{V_{cMax}(V_{cMin}-V_{ref})-V_{cMin}(V_{cMax}-V_{ref})}{R_3}$$

Isolate R3 and define it using given terms.

$$R_3=\left(\frac{V_{cMax}(V_{cMin}-V_{ref})-V_{cMin}(V_{cMax}-V_{ref})}{V_{cMax}(V_{inMin}-V_{cMin})-V_{cMin}(V_{inMax}-V_{cMax})}\right)(R_1)$$

Expand.

$$R_3=\left(\frac{V_{cMin}V_{cMax}-V_{cMin}V_{cMax}+V_{cMin}V_{ref}-V_{cMax}V_{ref}}{V_{inMin}V_{cMax}-V_{cMin}V_{cMax}-V_{cMin}V_{inMax}+V_{cMin}V_{cMax}}\right)(R_1)$$

Simplify the numerator.

$$R_3=\frac{(V_{cMin}-V_{cMax})(V_{ref})(R_1)}{V_{inMin}V_{cMax}-V_{cMin}V_{cMax}-V_{cMin}V_{inMax}+V_{cMin}V_{cMax}}$$

Add zero to denominator.

$$R_3=\frac{(V_{cMin}-V_{cMax})(V_{ref})(R_1)}{V_{inMin}V_{cMax}-V_{cMin}V_{cMax}-V_{cMin}V_{inMax}+V_{cMin}V_{cMax}+(0)}$$

$$R_3=\frac{(V_{cMin}-V_{cMax})(V_{ref})(R_1)}{V_{inMin}V_{cMax}-V_{cMin}V_{cMax}-V_{cMin}V_{inMax}+V_{cMin}V_{cMax}+(V_{cMax}V_{inMax}-V_{cMax}V_{inMax})}$$

Simplify the denominator

$$R_3 = \frac{\left(V_{cMin} - V_{cMax}\right)\left(V_{ref}\right)\left(R_1\right)}{V_{cMax}\left(V_{inMin} - V_{inMax}\right) + V_{inMax}\left(V_{cMax} - V_{cMin}\right)}$$

Multiply by 1.

$$R_3 = \left(\frac{\left(V_{cMin} - V_{cMax}\right)\left(V_{ref}\right)\left(R_1\right)}{V_{cMax}\left(V_{inMin} - V_{inMax}\right) + V_{inMax}\left(V_{cMax} - V_{cMin}\right)}\right)(1)$$

$$R_3 = \left(\frac{\left(V_{cMin} - V_{cMax}\right)\left(V_{ref}\right)\left(R_1\right)}{V_{cMax}\left(V_{inMin} - V_{inMax}\right) + V_{inMax}\left(V_{cMax} - V_{cMin}\right)}\right)\left(\frac{\frac{-1}{V_{inMax} - V_{inMin}}}{\frac{-1}{V_{inMax} - V_{inMin}}}\right)$$

$$R_3 = \frac{\left(\frac{V_{cMax} - V_{cMin}}{V_{inMax} - V_{inMin}}\right)\left(V_{ref}\right)\left(R_1\right)}{V_{cMax} - V_{inMax}\left(\frac{V_{cMax} - V_{cMin}}{V_{inMax} - V_{inMin}}\right)}$$

$$R_3 = \frac{\left(m\right)\left(V_{ref}\right)\left(R_1\right)}{b}$$

2. EQUATION FOR R2 DERIVATION

Subtract min case equation from max case equation.

$$\frac{V_{inMax} - V_{cMax}}{R_1} = \frac{V_{cMax}}{R_2} + \frac{V_{cMax} - V_{ref}}{R_3}$$

$$\frac{V_{inMin} - V_{cMin}}{R_1} = \frac{V_{cMin}}{R_2} + \frac{V_{cMin} - V_{ref}}{R_3}$$

$$\left(\frac{V_{inMax} - V_{cMax}}{R_1}\right) - \left(\frac{V_{inMin} - V_{cMin}}{R_1}\right) = \left(\frac{V_{cMax}}{R_2} + \frac{V_{cMax} - V_{ref}}{R_3}\right) - \left(\frac{V_{cMin}}{R_2} + \frac{V_{cMin} - V_{ref}}{R_3}\right)$$

$$\frac{V_{inMax} - V_{cMax} - V_{inMin} + V_{cMin}}{R_1} = \frac{V_{cMax} - V_{cMin}}{R_2} + \frac{V_{cMax} - V_{ref} - V_{cMin} + V_{ref}}{R_3}$$

$$\frac{\left(V_{inMax}-V_{inMin}\right)-\left(V_{cMax}-V_{cMin}\right)}{R_1}-\frac{V_{cMax}-V_{cMin}}{R_3}=\frac{V_{cMax}-V_{cMin}}{R_2}$$

Isolate R2

$$R_2=\frac{R_1R_3\left(V_{cMax}-V_{cMin}\right)}{R_3\left(V_{inMax}-V_{inMin}\right)-R_3\left(V_{cMax}-V_{cMin}\right)-R_1\left(V_{cMax}-V_{cMin}\right)}$$

Multiply by 1.

$$R_2=\left(\frac{R_1R_3\left(V_{cMax}-V_{cMin}\right)}{R_3\left(V_{inMax}-V_{inMin}\right)-R_3\left(V_{cMax}-V_{cMin}\right)-R_1\left(V_{cMax}-V_{cMin}\right)}\right)(1)$$

$$R_2=\left(\frac{R_1R_3\left(V_{cMax}-V_{cMin}\right)}{R_3\left(V_{inMax}-V_{inMin}\right)-R_3\left(V_{cMax}-V_{cMin}\right)-R_1\left(V_{cMax}-V_{cMin}\right)}\right)\left(\frac{\frac{-1}{V_{inMax}-V_{inMin}}}{\frac{-1}{V_{inMax}-V_{inMin}}}\right)$$

$$R_2=\frac{R_1R_3\left(\frac{V_{cMax}-V_{cMin}}{V_{inMax}-V_{inMin}}\right)}{R_3-R_3\left(\frac{V_{cMax}-V_{cMin}}{V_{inMax}-V_{inMin}}\right)-R_1\left(\frac{V_{cMax}-V_{cMin}}{V_{inMax}-V_{inMin}}\right)}$$

$$R_2=\frac{R_1R_3\left(\frac{V_{cMax}-V_{cMin}}{V_{inMax}-V_{inMin}}\right)}{R_3-\left(R_3+R_1\right)\left(\frac{V_{cMax}-V_{cMin}}{V_{inMax}-V_{inMin}}\right)}$$

$$R_2=\frac{R_1R_3m}{R_3-\left(R_3+R_1\right)m}=\frac{mR_1R_3}{R_3-m\left(R_3+R_1\right)}$$