PAC194X/5X System Performance and Verification

Author: *Todd Wimer*
Microchip Technology Inc.

INTRODUCTION

The PAC194X/5X product family are highly accurate measurement devices for voltage, current and power. When designing based on a product in this family, there are several factors to consider.

The product configuration determines measurement magnitude and resolution. The product performance defines the system tolerances. A key product feature to understand is the offset correction that uses a short variability over a small number of readings to provide an accurate average result. To maximize the system performance and accuracy, ensure system design is focused on the connections to the shunt resistor (sense resistor, R_{SENSE}). The system configuration and performance determine the ability to verify the product. Additionally, to ensure correct measurements, consider the system connections to the product.

This document examines how these factors impact system performance and design and provides suggestions to help minimize issues with the design and time to market.

PAC194X/5X CONFIGURATION

Devices in the PAC194X/5X family perform highly accurate voltage and current measurements using two 16-bit Analog-to-Digital Converters (ADCs). One of these measurements is the power line or bus voltage, V_{BUS}. The other is the current measurement, calculated from V_{SENSE} measured across R_{SENSE} when current passes through the resistor placed between the Sense*X*+ and Sense*X*– pins of PAC194X/5X. The impact of the product configuration on measurement performance is explained in this section. The main difference between the PAC194X and the PAC195X is the V_{BUS} ADC full-scale range. For PAC194X, the full-scale range is 9V, while for PAC195X is 32V. While the examples provided in this document use the PAC195X specifications, the presented functionality is virtually identical for PAC194X.

The bus voltage, V_{BUS}, is directly measured through the Sense*X*+ pin. Products in the PAC194X/5X family have up to four channels. Each channel is composed of two pins: Sense*X*+ and Sense*X*–, where *X* denotes the channel: 1–4. Sense*X*+ is connected to the supply side of the sense resistor, while Sense*X*– is connected to the load side of the sense resistor. Determining the bus voltage is a single-ended measurement with respect to the ground.

The PAC195X has three voltage ranges:

- Unipolar range of 0V to +32V
- Bipolar range of -16V to +16V
- Bipolar range of -32V to +32V

Use Equation 1 to calculate the voltage resolution of individual ranges. The voltage range is divided by the maximum ADC output, 2^{16}, where 16 refers to the ADC's 16 bits of resolution.

EQUATION 1:

$$V_{RESOLUTION} = \frac{V_{RANGE}}{2^{16}}$$

Where:

$V_{RESOLUTION}$ = Voltage Resolution (µV/LSB)
V_{RANGE} = Voltage Range (V)

Use Equation 2 to determine the ideal ADC output value. The measured bus voltage is divided by the voltage resolution as calculated in Equation 1.

EQUATION 2:

$$ADC_{Output} = \frac{V_{BUS}}{V_{RESOLUTION}}$$

Where:

ADC_{Output} = ADC Output Code (LSB)
V_{BUS} = Bus Voltage Magnitude (V)
$V_{RESOLUTION}$ = Voltage Resolution (µV/LSB)

For example, Table 1 shows the ideal ADC output codes when measuring $V_{BUS} = 12.435V$.

TABLE 1: BUS VOLTAGE RESOLUTION AND IDEAL ADC OUTPUT FOR V_{BUS} = 12.435V

V_{BUS} Range	$V_{Resolution}$	Ideal ADC Output
Unipolar 0-32V	488 µV/LSB	25467 LSB
Bipolar ±16V	976 µV/LSB	12733 LSB
Bipolar ±32V	488 µV/LSB	25467 LSB

The current measurement is implemented as a differential voltage measurement across the sense resistor. The differential voltage measurement uses the Sense*X*+ and Sense*X*– pins on the device.

R_{SENSE} is named after its application to sense or measure a current. Selecting the resistance is a critical design decision for the system. To select the correct sense resistance, make sure to consider the system measurement range and resolution requirements. Using the maximum current for the system, I_{MAX}, the required resistance is calculated using the magnitude of the PAC195X voltage ranges, V_{RANGE} (see Table 2).

TABLE 2: PAC195X VOLTAGE RANGES

V_{RANGE} (mV)	$V_{MAGNITUDE}$ (mV)
±50	50
0-100	100
±100	100

Rearranging the terms in Ohm's law, the sense resistance is calculated from the voltage magnitude and the maximum current, as shown in Equation 3.

EQUATION 3:

$$R_{SENSE} = \frac{V_{MAGNITUDE}}{I_{MAX}}$$

Where:

R_{SENSE} = Sense Resistance (mΩ)
$V_{MAGNITUDE}$ = Voltage Magnitude (mV)
I_{MAX} = Maximum Current (A)

Use Equation 4 to calculate the current resolution. The range of the currents is divided by the maximum ADC output, 2^{16}, where 16 refers to the ADC's 16 bits of resolution. I_{RANGE} is equal to:

- I_{MAX} for unipolar mode
- $2 \times I_{MAX}$ for bipolar modes

EQUATION 4:

$$I_{RESOLUTION} = \frac{I_{RANGE}}{2^{16}}$$

Where:

$I_{RESOLUTION}$ = Current Resolution (mA/LSB)
I_{RANGE} = Current Range (A)

Using the current resolution, the Ideal ADC Output code is calculated by dividing the input current by the current resolution. For example, a 15.673A current results in the Ideal ADC Output codes shown in Table 3, where the sense resistance is calculated for different maximum current values.

TABLE 3: R_{SENSE} VALUES FOR DIFFERENT MAXIMUM CURRENTS

PAC194X/5X V_{RANGE} (mV)	I_{MAX} (A)	R_{SENSE} (mΩ)	I_{RANGE} (A)	$I_{RESOLUTION}$ (mA/LSB)	Ideal ADC Output Code (LSB)
±50	100	0.5	200	3	5136
0-100	100	1	100	1.5	10271
±100	100	1	200	3	5136
±50	20	2.5	40	0.6	25679
0-100	20	5	20	0.3	51357
±100	20	5	40	0.6	25679

PAC194X/5X PERFORMANCE

The current range and resolution values shown in Table 3 are the ideal performance for ADCs in the PAC194X/5X product family. The overall performance includes an offset error, gain error, noise and temperature drift. The data sheet has performance curves that reflect the typical performance including all these error sources (see Figure 1, Figure 2 and Figure 3). The errors are expressed as percentages of the full-scale. The voltage error is calculated as shown in Equation 5.

EQUATION 5:

$$V_{ERROR} = V_{SPAN} \times E_{PERCENT}$$

Where:

V_{ERROR} = Sense Voltage Error (mV)
V_{SPAN} = Sense Voltage Span (mV)
$E_{PERCENT}$ = Sense Voltage Percent Error (%)

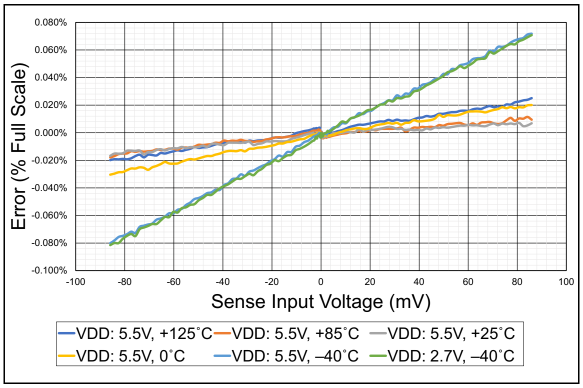

FIGURE 1: V_{SENSE} Error vs. V_{SENSE} Input Voltage, Bipolar Mode.

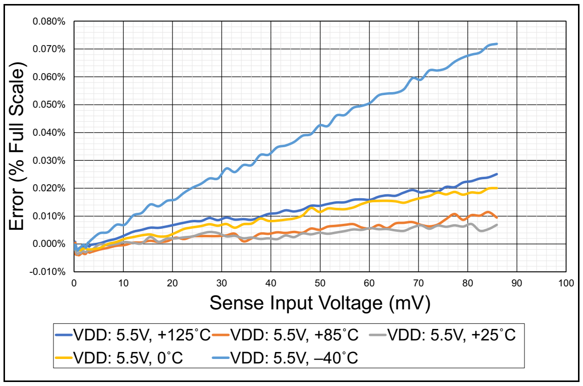

FIGURE 2: V_{SENSE} Error vs. V_{SENSE} Input Voltage, Unipolar Mode.

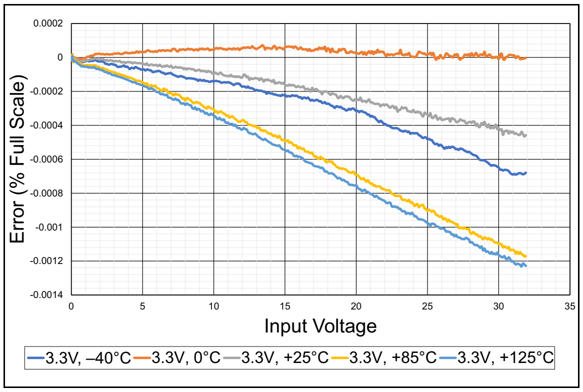

FIGURE 3: V_{BUS} Error vs. V_{BUS} Input Voltage.

The sense voltage spans are as following:

- 100 mV for the 0-100 mV and ±50 mV sense voltage ranges
- 200 mV for the ±100 mV sense voltage range

The bus voltage spans are as following:

- 32V for the 0–32V and ±16V bus voltage ranges
- 64V for the ±32V bus voltage range

For example, an error of 0.02% for V_{SENSE} calculated using Equation 5 results in the values show in Table 4.

TABLE 4: SENSE VOLTAGE ERROR IN VOLTAGE CALCULATIONS

V_{ERROR} (µV)	$E_{PERCENT}$ (%)	V_{SPAN} (mV)
20	0.02	100
40	0.02	200

Figure 1 and Figure 2 show that the typical V_{SENSE} error is less than 0.1% or 100 µV and 200 µV for voltage spans of 100 mV and 200 mV, respectively. Figure 3 shows the V_{BUS} error is less than 0.15% or 48 mV and 96 mV for voltage spans of 32V and 64V, respectively.

The results shown in Figure 1, Figure 2 and Figure 3 are optimized for offset. The PAC194X/5X product family has an offset cancellation routine. If unaveraged samples are examined, a pattern around zero is observed (see Figure 4). In this figure, the unaveraged samples are the Permute 1-4 results and the averaged result is the Permute On value in the center of the chart. When averaged, this pattern results in a near 0 LSB offset.

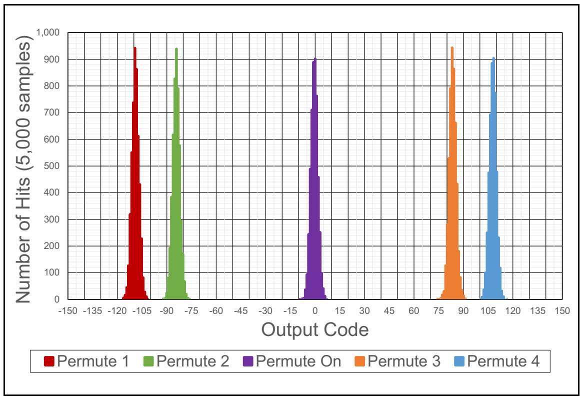

FIGURE 4: *Four Permute Combinations and Resulting Low Average Offset (Permute On).*

There are three methods used to average the results:

1. Read the average result register. This register internally performs the averaging of eight samples and stores the average result.
2. Collect many samples and average them by the host (microcontroller or other device using the measurement results from PAC194X/5X).
3. Use the accumulator function on the Integrated Circuit (IC) that can amass many samples.

For the third method, after amassing the desired number of samples, the host can divide the accumulator register by the accumulator count register to obtain the average. This reduces the load on the host compared to other methods. For the second and third methods, either a significant number of samples (over 30) or a number divisible by eight are required to avoid skewing the results.

SENSE RESISTOR CONNECTION

There are several challenges when measuring current using a sense resistor. Following are the common areas where these challenges appear and methods to minimize their impact. Note that the following is not an exhaustive list.

When measuring currents with a sense resistor, it is important to minimize the impact of the resistance on the voltage supplied to the load. To do this usually requires using the smallest resistance possible with typical values smaller than 10 mΩ. For PAC194X/5X, there is a near 0A current into the Sense*X*+ and Sense*X*– pins (see Figure 5). With these small resistances, it is important to consider the impact of the connections on the circuit board. The trace resistances can alter the voltage measured across the Sense*X*+ and Sense*X*– pins and leads to a measurement that is across a higher resistance than excepted. This measurement distorts the current calculation and results in a value that is larger than anticipated. The rest of this section examines some of the potential sources of additional trace resistance.

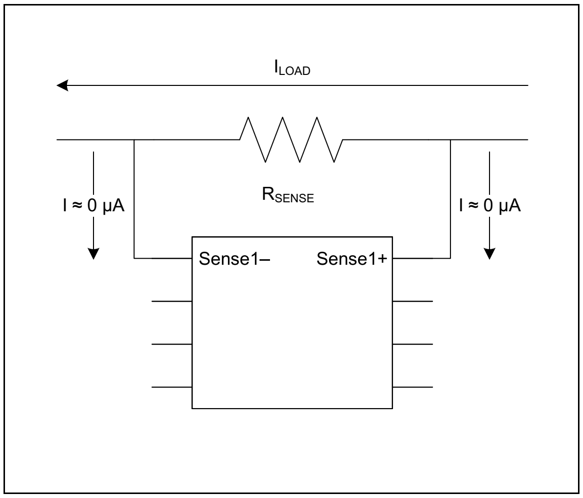

FIGURE 5: *Correct Schematic Connections.*

Figure 6 shows where an additional trace impedance can alter the R_{SENSE} value and where a proper connection must be routed. The trace impedance adds an additional trace resistance, R_{TRACE}, to the sense resistor and PAC194X/5X measures the current over this trace resistance. The correct layout has two traces (labeled Sense*X*+ and Sense*X*– in Figure 6) directly connected to the sense resistor and to the Sense*X*+ and Sense*X*– pins of PAC194X/5X.

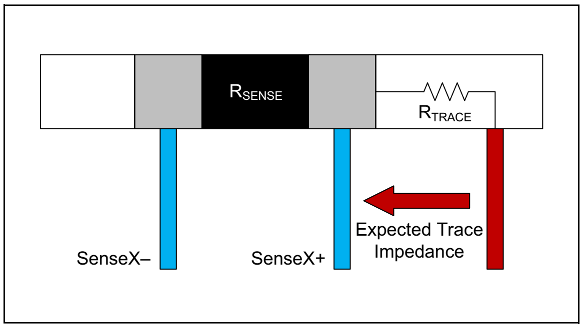

FIGURE 6: *Correct Layout with Trace Impedance.*

Trace impedance can occur from the layout. Microchip recommends drawing the schematic depicting the trace impedance. A schematic can have R_{SENSE} connections that appear to be directly across the resistor. Examining the current flow in a schematic can identify locations where this trace impedance may occur. In Figure 7, Figure 8 and Figure 9 the connections to the Sense*X*+ and Sense*X*– pins suggest connections at different points along the V_{BUS} power rail.

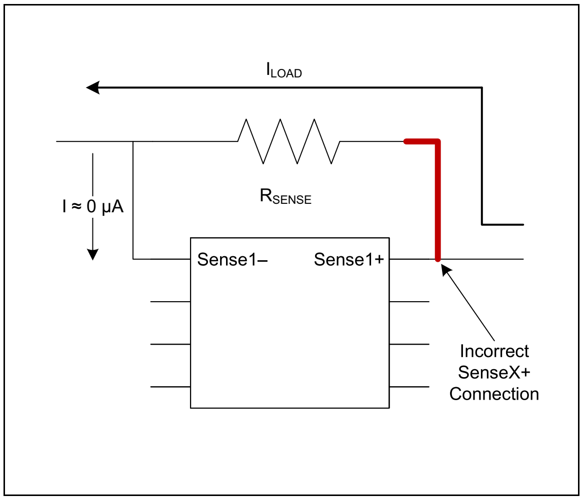

FIGURE 7: *Incorrect SenseX+ Connection.*

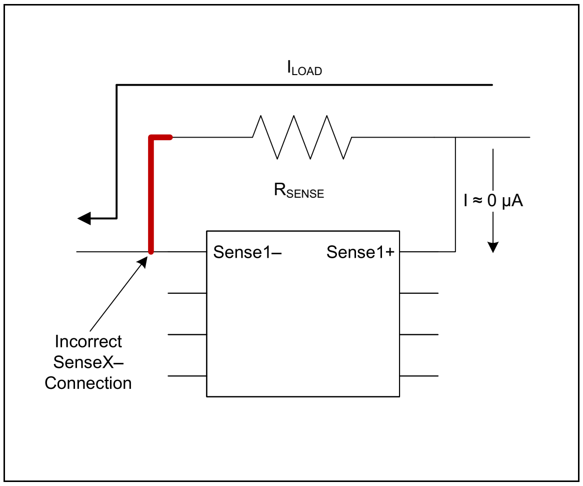

FIGURE 8: *Incorrect SenseX– Connection.*

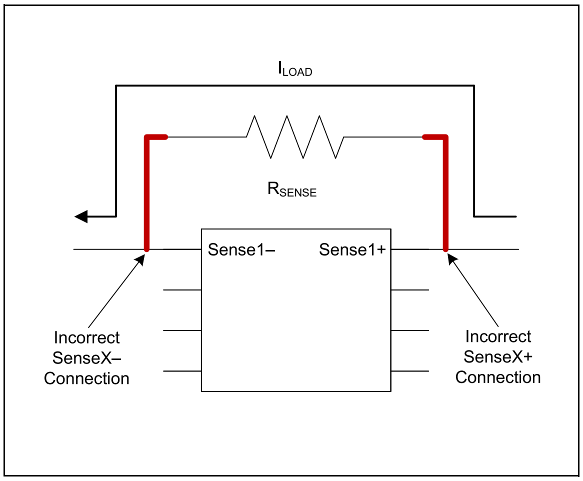

FIGURE 9: *Incorrect SenseX+ and SenseX– Connections.*

In these figures, it is important to directly connect the traces from PAC194X/5X to the sense resistor. This can be done by directly connecting the trace impedance to the pads as seen in Figure 10.

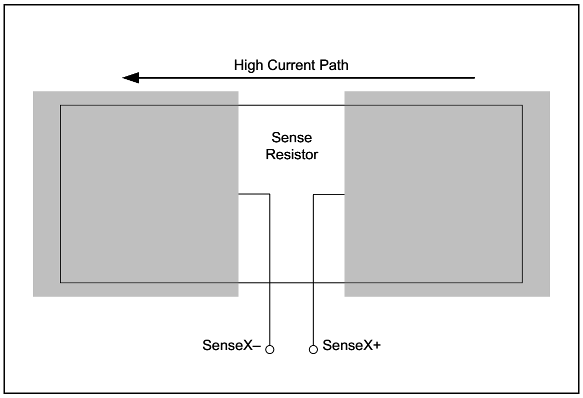

FIGURE 10: *Two Terminal Connection Pad Layout.*

Microchip recommends the layout shown in Figure 11. This layout benefits from a separate connection for the voltage measurement to reduce the impact of high current flowing through the resistor. It is important to keep the voltage measurement traces small to reduce temperature impact since the copper on the board varies more than most high-precision resistors. In some cases, this is not enough and a resistor with a built-in Kelvin connection is required. These resistors are four-terminal devices with two connections for the current flow and two connections for the sense lines. Microchip recommends that the traces used in any of the presented layouts are differential traces that match the impedances and trace lengths. Mismatches in the traces cause offset or gain errors due to a small current that flows between the pin and the resistor. As the resistances get smaller, the solder resistance also impacts the resistance at the PAC194X/5X inputs.

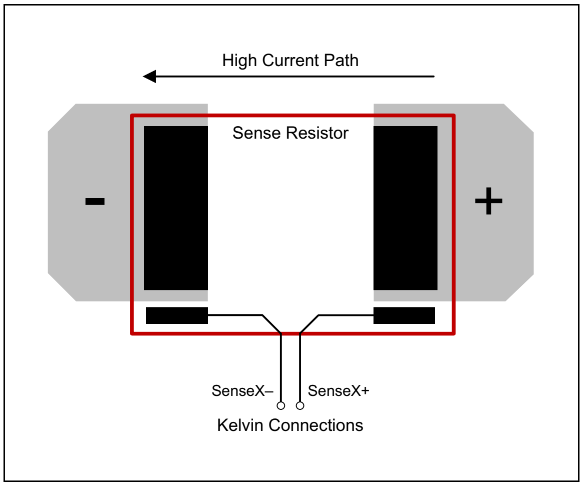

FIGURE 11: *Kelvin Layout with Four Terminal Connections.*

PERFORMANCE VERIFICATION

When the connections to the sense resistor are optimized and it is time to verify the measurement, it is important to consider the test equipment specifications, performance and connections. The typical test equipment used to verify current and voltage measurements is a digital multimeter (DMM).

Just like for PAC194X/5X, make sure to consider the measurement range and resolution of the equipment used to verify the product results. For example, consider the following test equipment: PXI-4071 and USB-6003 from National Instruments. PXI-4071 has five voltage ranges: 100 mV, 1V, 10V, 100V and 1 kV, while USB-6003 has only a voltage range of ±10V. The range of USB-6003 is less than the full-scale range of PAC195X and can be insufficient to verify the performance of PAC195X across the full V_{BUS} range.

The resolutions for PXI-4071 are: 10 nV, 100 nV, 1 µV, 10 µV and 100 µV. The resolution specifications of PXI-4071 are significantly better than PAC195X. USB-6003 is a 16-bit device like PAC194X/5X. The resolution for USB-6003 is calculated using Equation 4, resulting in a value of 305 µV. The resolution of USB-6003 is comparable to the V_{BUS} resolution of PAC195X, but it is significantly larger than the V_{SENSE} resolution of PAC195X.

Microchip recommends using test equipment with specifications ten times better than PAC195X. However, this is not a requirement. Based on the presented scenario, Microchip recommends selecting PXI-4071 to verify the results of PAC195X measurements, and not USB-6003.

Additionally, test equipment has errors associated with the measurement. The specifications are often different than the specifications of PAC195X. PXI-4071 specifies measurement accuracy as parts per million (ppm) of reading and of range and how it varies over time. For typical use cases, 100 mV is 5 ppm of the reading and an additional 4 ppm of the range, while 100V is 5 ppm of the reading and 2 ppm of the range. The worst-case error for 100 mV is 0.00009%. For a configuration using the 100V range that covers the full 32V range of PAC195X, the error is 0.011%. When comparing these errors to the PAC195X errors displayed in Figure 1, Figure 2 and Figure 3, it shows that PXI-4071 is better than PAC195X, making PXI-4071 a good option to verify the PAC195X results.

The PXI-4071 specifications mention an integral nonlinearity (INL) of ±1.8 LSB. This proves that PXI-4071 is linear across the range. However, considering the absolute errors, this is not a factor in determining the capability of the test equipment.

USB-6003 specifies an absolute accuracy of typically 6 mV with a maximum overtemperature of 26 mV. Converting these values to percentages shows that measuring a signal of 100 mV generates errors between 6% and 26% that are insufficient to verify the PAC195X results. For a maximum signal of 10V, the errors are between 0.06% and 0.26%. They are higher than the errors from Figure 1, Figure 2 and Figure 3, and therefore insufficient to verify the PAC195X results.

Considering these measurement errors, PXI-4071 is capable equipment, while USB-6003 does not produce reliable results when verifying the high-performance requirements of PAC195X.

The instrument connections are also important when verifying the performance of PAC195X. It is critical to ensure that no additional impedances are included when connecting the leads of the equipment to the sense resistor. To do this, connect the leads to the ends of the resistor, preferably by soldering the leads to the connections of the Sense*X*+ and Sense*X*– pins. Do not solder the leads to the pads, because it can impact the measurements by including additional resistance.

Measuring the sense resistor in most applications also requires a Kelvin connection. In this case, the test equipment has to be capable of 4-point measurements. A known current is applied into two of the four terminals. The connection for these two terminals is not required to be directly connected to the ends of the sense resistor because the applied current creates a voltage across the resistor that is accurately measured. The two terminals that measure the voltage have to be directly connected across the resistor to ensure that only the resistance is measured.

Figure 12 shows the integration time of PXI-4071, in number of power line cycles (NPLC), against the root mean square (RMS) noise, in ppm of range. As shown, a longer integration time can significantly reduce measurement noise. While this applies to PAC194X/5X as well, the device can also improve measurement results by integrating them using the accumulation register.

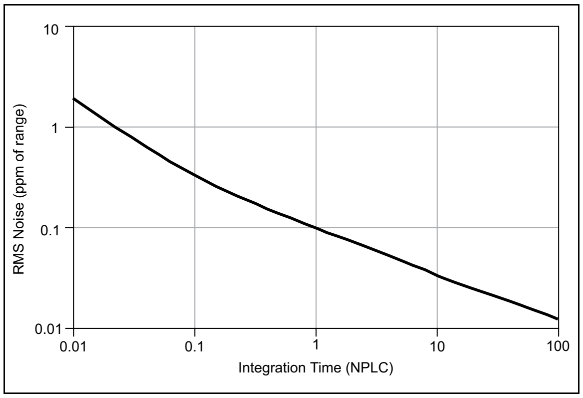

FIGURE 12: *PXI-4071 RMS Noise vs. Integration Time.*

CONCLUSION

The PAC194X/5X device family are extremely accurate instruments for measuring voltage and current. To precisely measure these two parameters, ensure that the measurement is performed correctly. To do this, confirm that the printed circuit board schematic and layout do not have unnecessary impedances that can negatively impact the measurement. Also, verify that the selection of components meets the requirements for measurement resolution, range and device settings. The same considerations for system design need to be applied when verifying the PAC194X/5X results.

When all previously mentioned items are considered, the PAC194X/5X device family provides a precise voltage and current measurement that can be independently verified by a high-precision test equipment to ensure accuracy.

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