ON Semiconductor

Design Note – DN05117/D

Accurate Shunt Resistor Connections for Optimum Performance with the ON Semiconductor NCS21xR Current Sense Amplifiers (CSA's)

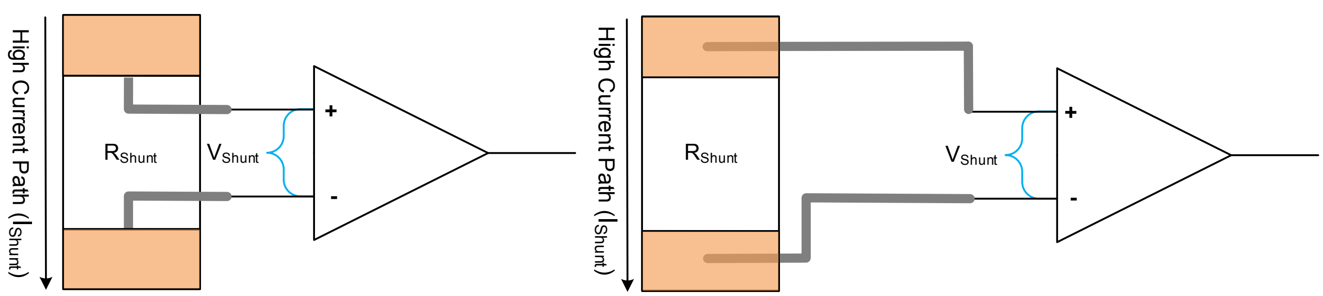
Device	Application	R_{Shunt}	Input (I_{Shunt})	Output Voltage (V_{OUT})	Input Offset Voltage	Package
NCS213R	High Side Current Sensing	1 mΩ	0 to 10 A	1.65 V to 2.15 V	±100 µV	SC70-6, UQFN10

Circuit Description

This design note describes how to implement an optimum shunt resistor connection based on the shunt resistor manufacturer's recommendations in order to get optimum performance when using the NCS21xR series current sense amplifiers.

An important factor to keep in mind is that the NCS213R current sense amplifier is actually detecting a voltage potential across its differential inputs and is accurately amplifying a voltage, not a current; thus the current is measured indirectly. Using the measured output voltage, the amplifier gain, the reference voltage, and the value of the shunt resistor, the current flowing through the shunt resistor can be calculated:

- $V_{OUT} = (I_{Shunt} \text{ x } R_{Shunt})\text{Gain} + V_{REF}$
- $I_{Shunt} = \frac{V_{OUT} - V_{REF}}{(R_{Shunt})(\text{Gain})}$



Ideal Connection to Shunt Resistor

- ✓ Traces are uniform, equal length, equal dimension
- ✓ Connection of sense traces at manufacturer recommended location for accurate measurement
- ✓ The voltage measured by the amplifier corresponds exactly to the drop across the active portion of the shunt

Non-Ideal Connection to Shunt Resistor

- ✓ Traces are too long, unequal length, not uniform
- ✓ Sense trace connection to shunt is at a location where stray resistance of the copper lead will affect measurement
- ✓ The voltage measured includes additional error voltages across the copper end contacts of the shunt

Figure 1: Ideal vs Non-Ideal Shunt Resistor Connections

Shunt Resistor Design

It is useful to understand the architecture of a current shunt in order to get maximum accuracy. The ends of the shunt that get soldered down are usually copper material. The shunt itself is a different material such as Manganin, and it is this center section material that the shunt manufacturer is trimming to an exact value. The objective is to accurately capture the voltage drop across the resistor material itself and none of the voltage drop in the end connections. Figure 2 shows the typical manufacturer recommended connection points for a two terminal shunt resistor. The sense trace connections are in the middle of either side, right at the plane of where the shunt resistor material interfaces with the copper lead.

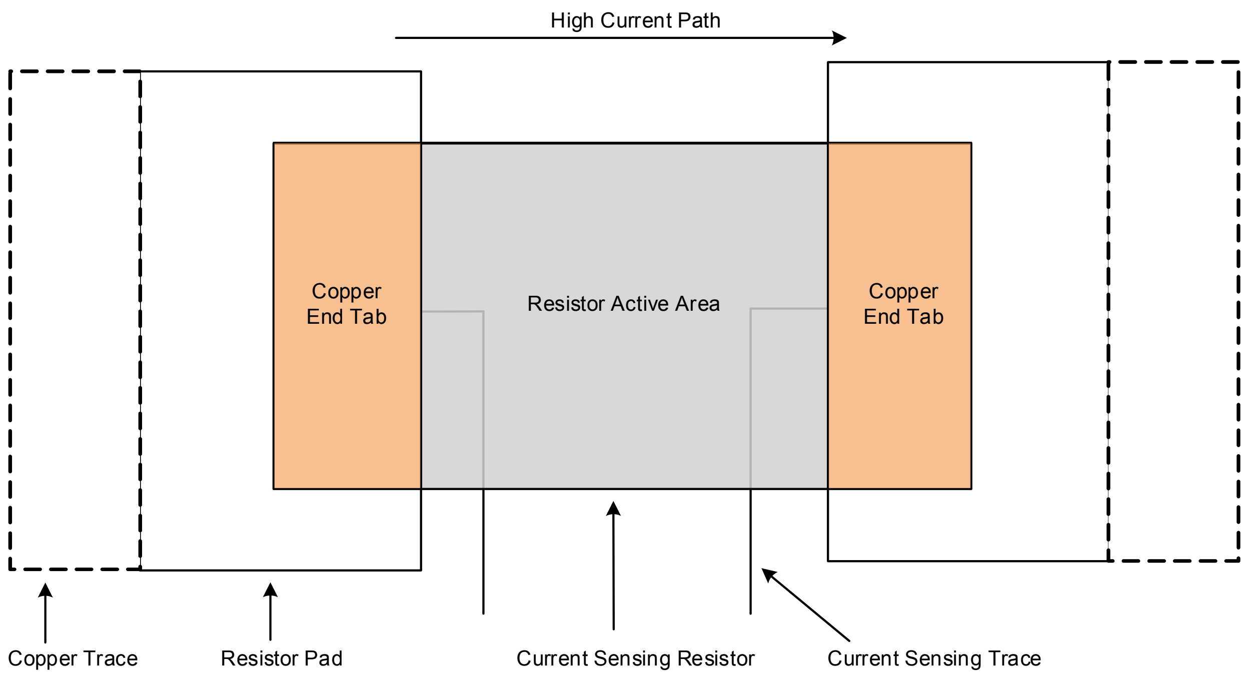


Figure 2: Typical Manufacturer Recommended Connection for a Two Terminal Shunt Resistor

Always follow the shunt manufacturer's recommendations on connecting to the shunt, in the event that they are different from those highlighted in Figure 2. Notice in Figure 3 that the stray lead resistance and stray sense trace resistance is depicted. An improper connection will add these unwanted stray resistances to the measurement and increase error.

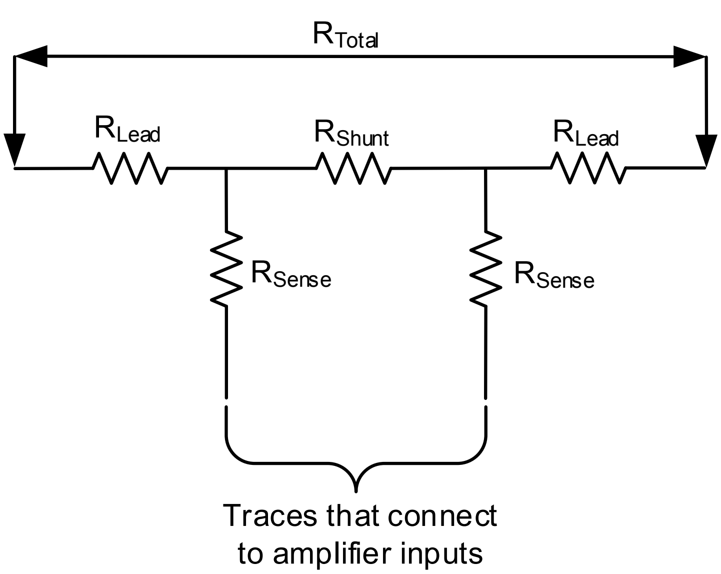


Figure 3: Connection to a Two Terminal Shunt Resistor Depicting Stray Resistances (R_{Lead} and R_{Sense})

The four terminal shunt resistor shown in Figure 4 provides a more straight forward way to connect the Kelvin sense traces to the shunt and maintain a high level of accuracy; however, there is a cost penalty for a four terminal shunt resistor.

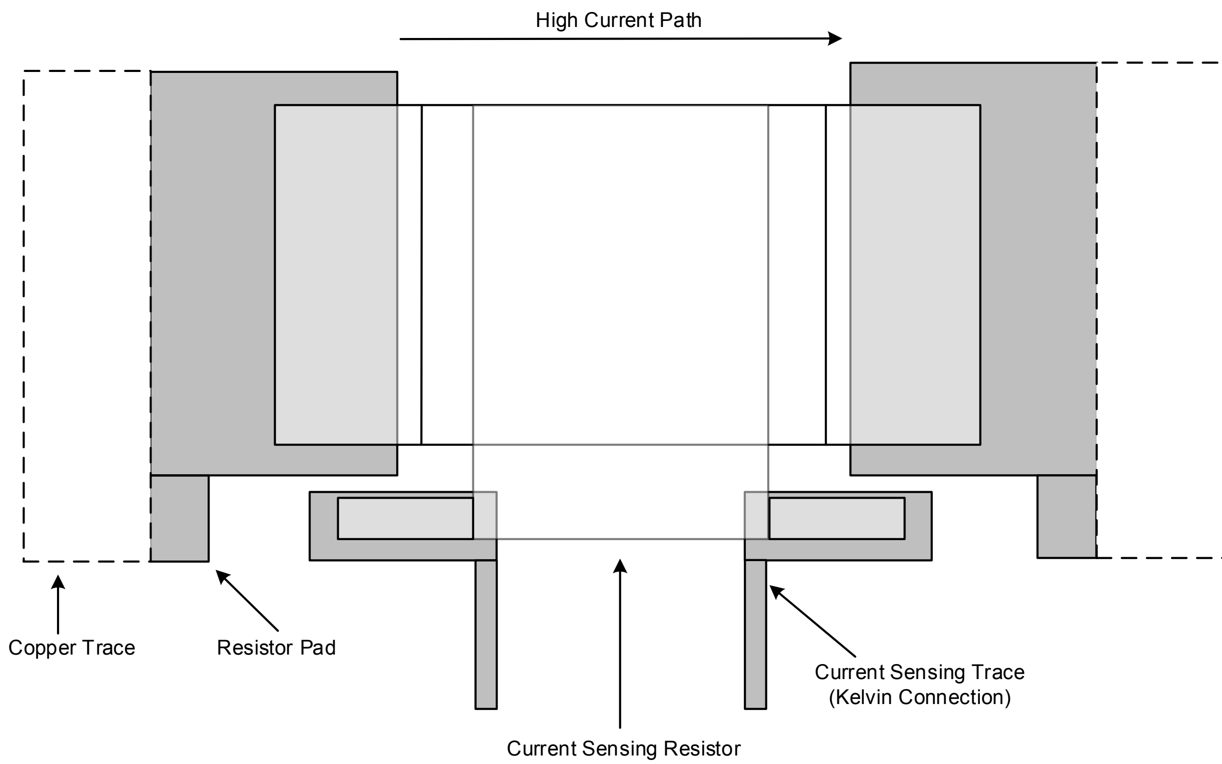


Figure 4: Typical Manufacturer Recommended Shunt Connection for a Four Terminal Shunt Resistor

Diagnosing Shunt Current Measurement Errors

The bulleted list below, Figure 5, and Table 1 can be used in diagnosing shunt current measurement errors for any current sense amplifier circuit.

- Current Sense Amplifiers are voltage amplifiers.
- Measure the voltage directly at the amplifier input pins. The results may be different than when measured across the resistor.
- The amplifier output should be the measured voltage directly across the inputs (V_{Shunt}) multiplied by the amplifier gain.
- Most often problems prove to be related to shunts and or shunt connections.

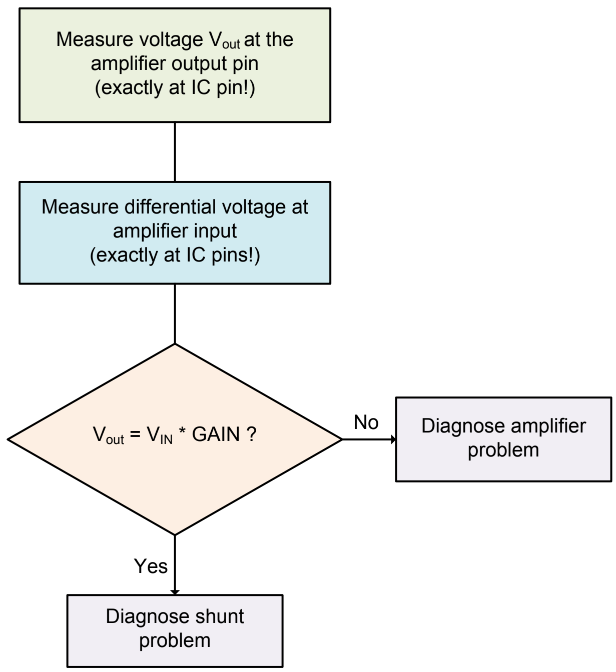


Figure 5: Shunt Current Measurement Error Diagnosis Decision Tree

Using the Shunt Current Measurement Debug Table in Table 1, it may be realized that the voltage measured directly across the amplifier input pins compared to the voltage measured directly across the shunt resistor is different by enough of an amount to cause errors that are unacceptable. In other words, the amplifier is accurately amplifying the wrong voltage! The final error at the output could easily be on the order of 10% to 15% or more due to poor PCB layout and connection to the shunt. The NCS213R is going to accurately amplify the voltage that it sees directly at its inputs pins.

Table 1: Shunt Current Measurement Debug Table Example

I_{Shunt} (A)	Measured Voltage Directly Across IN+ and IN- Pins (V_{IN}) (V)	Measured Voltage Directly Across R_{Shunt} (V)	Measured Voltage Directly at OUT (V)	OUT (V) = V_{IN} x Gain? (Yes/No)
0				
1 …"n"				

The Shunt Connection

- Use recommended connections to the shunt resistor. The connection traces should be of equal length, equal dimension and as short as possible.
- The current sense amplifier and the shunt resistor should both be on the same side of the PCB.
- Use four terminal (also known as Kelvin) shunts for the highest level of accuracy.

In Figure 6, the green box surrounds the area of the sense line traces from the shunt resistor to the input pins. The traces leading to the resistor pad are of equal length, dimension, and they terminate at the center of the inside of the pad relative to where the shunt resistor connects to the pad.

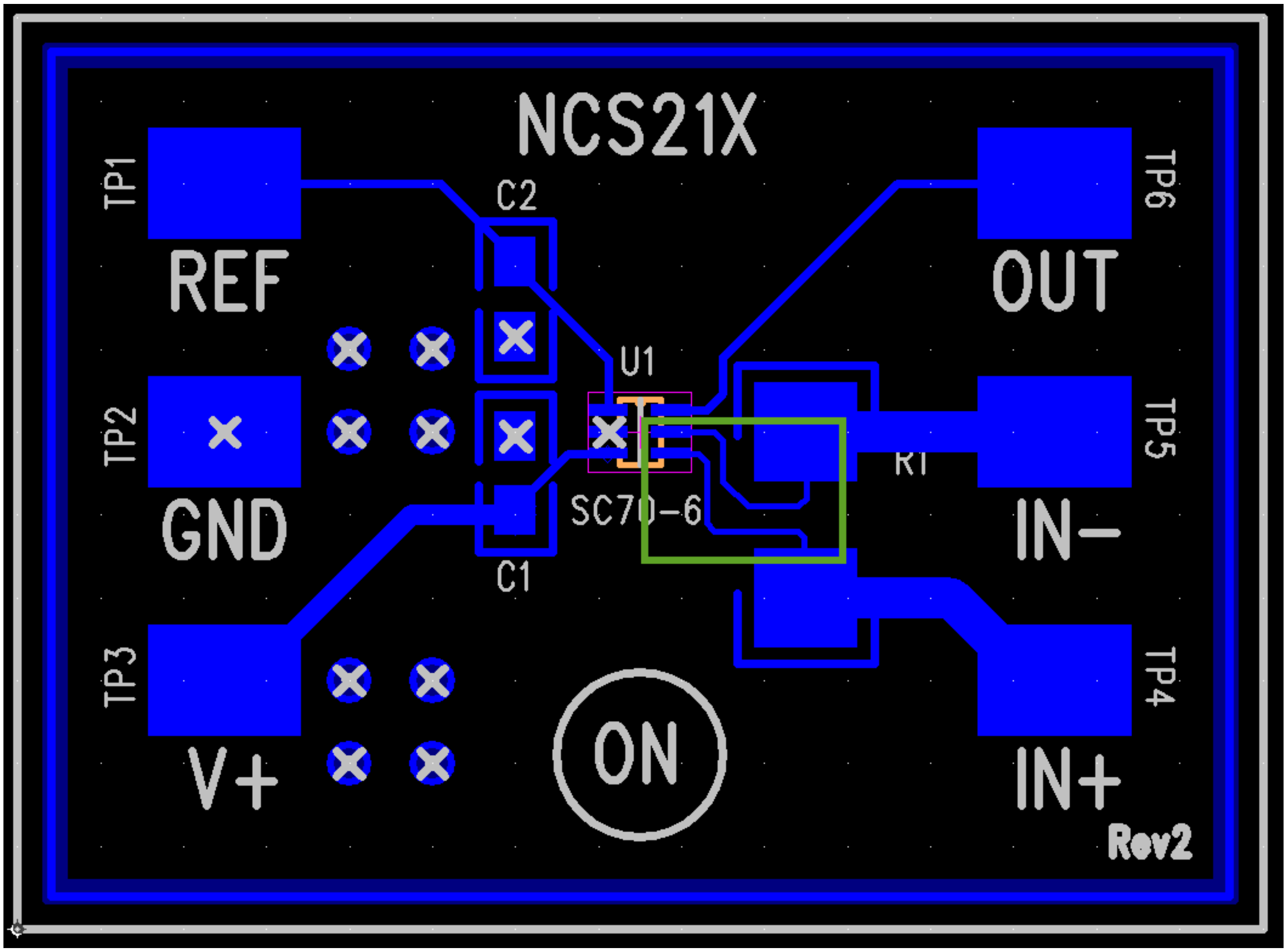


Figure 6: NCS21xR Customer Evaluation PCB Layout with Optimized Connections to Shunt Resistor

Figure 7 shows the two customer evaluation boards used for this current shunt measurement experiment. The board on the left, labeled "Good" has a 1 mΩ shunt soldered neatly across the resistor pads (R1) and the sense line connections are optimized based on typical manufacturer recommendations on how to connect to a two terminal shunt.

The board on the right, labeled "Bad" is configured exactly the same as the "Good" board, with the exception of the connection of the sense traces to the shunt. To illustrate the undesirable effects of an incorrect shunt connection, the sense lines were simply cut and rerouted to a different location on the sense resistor pads to emulate an incorrectly designed PC board connection.

For the most accurate voltage measurement across IN+ and IN-, use fine tip probes so that the actual input pins can be touched down upon. For accurate measurements on the shunt; since the exact location of the connection is underneath the shunt and is inaccessible, take the measurement on top of the shunt directly above the correct location shown in Figure 2. See Table 2 for measurement results.

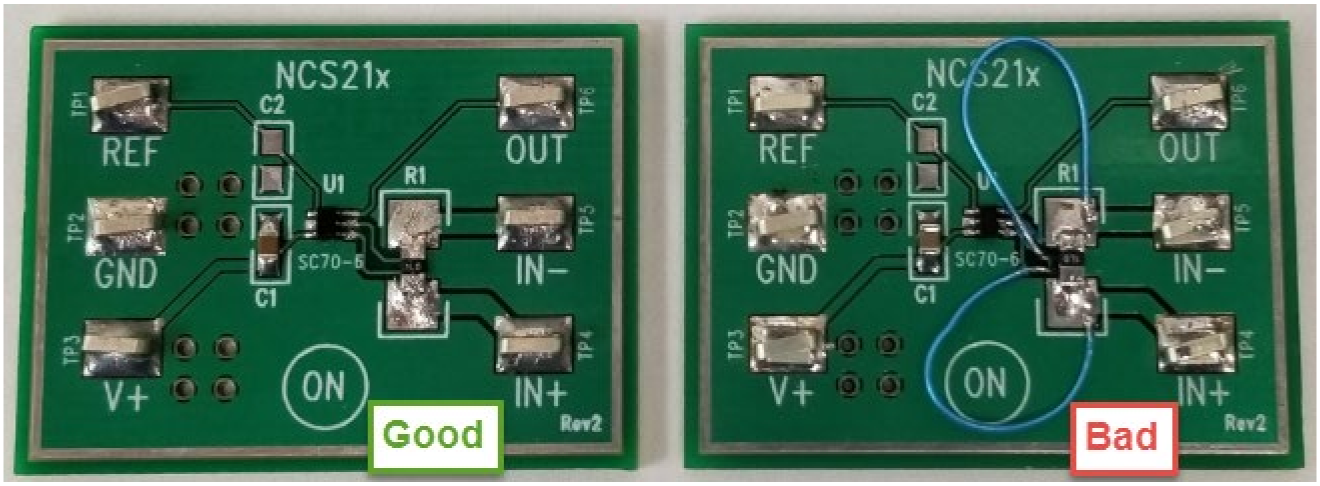


Figure 7: NCS213R Customer Evaluation Board; Good vs Bad Shunt Connections

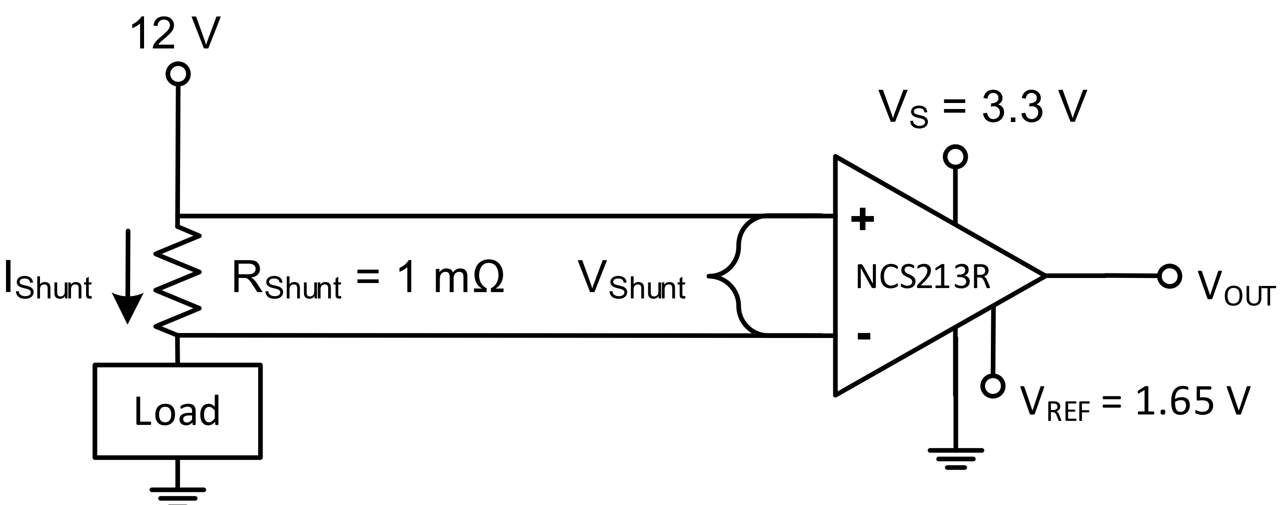


Figure 8: Schematic of NCS213R test circuit. The output quiescent voltage is 1.65 V

The measurement data in Table 2 was taken using the evaluation boards pictured in Figure 7. The current sense amplifier used was the NCS213R along with a 1 mΩ shunt resistor; see Figure 8 for circuit schematic. In Table 2, notice the "Measurement Error (%)" column for the "Good" connection – the measurement error from the ideal output voltage to the measured output voltage is very small, around one tenth of one percent; likewise, the difference in measurements directly at the input pins compared to measurements directly across the shunt are small, at most slightly over 0.1%. However, the "Bad" connection measurements show the error at almost 1.5% at 1 A and over 10% at 10 A.

Conclusion

The main point of this exercise was to illustrate that sense line connection to the shunt is not trivial and cannot be done haphazardly. It is evident from direct experimentation and observation that the non-optimized sense trace connections introduced unacceptable errors. Also of note on the "Bad" board, are the big discrepancies between the measurements taken at the input pins compared to measurements taken across the shunt. The measurements across the shunt were spot on and as expected, but not so with the measurements directly at the input pins. The voltage at the input pins was higher due to added stray resistance.

Table 2: Shunt Current Measurement Debug Table: Good vs Bad

I_{Shunt} (A)	Measured Voltage Directly Across IN+ and IN- Pins (mV)		Measured Voltage Directly Across R_{Shunt} (mV)		Measured Voltage Directly at OUT (V)		Ideal Output Voltage at OUT (V)	Measurement Error (%)	
	"Good" Connection	"Bad" Connection	"Good" Connection	"Bad" Connection	"Good" Connection	"Bad" Connection		"Good" Connection	"Bad" Connection
0	0.009	0.100	0.009	0.080	1.652	1.654	1.65	0.109	0.233
1	0.994	1.444	0.988	1.053	1.702	1.725	1.7	0.094	1.466
2	1.991	2.898	1.989	2.075	1.751	1.798	1.75	0.035	2.667
3	2.995	4.362	2.987	2.972	1.801	1.871	1.8	0.034	3.791
4	3.989	5.816	3.980	3.963	1.850	1.943	1.85	-0.016	4.791
5	4.996	7.307	4.950	4.994	1.900	2.018	1.9	-0.009	5.830
6	6.003	8.818	6.060	5.942	1.950	2.093	1.95	-0.002	6.847
7	7.001	10.317	6.950	6.915	1.999	2.168	2	-0.049	7.764
8	8.015	11.859	8.040	79.79	2.050	2.245	2.05	-0.004	8.685
9	9.045	13.464	8.981	9.005	2.101	2.326	2.1	0.029	9.708
10	10.043	15.085	10.025	9.965	2.150	2.406	2.15	0.013	10.634

Table 3 below highlights the NCS21xR and NCS199AxR series current sense amplifiers. Customer evaluation boards for each part number can be ordered at their respective landing pages.

Table 3: NCS21xR and NCS199AxR Series Current Sense Amplifiers

Part Number	Gain (V/V)	Input Offset Voltage (µV)	Gain Error (%)
NCS210R	200	±35 Max	±1
NCS211R	500	±35 Max	±1
NCS213R	50	±100 Max	±1
NCS214R	100	±60 Max	±1
NCS199A1R	50	±150 Max	±1.5
NCS199A2R	100	±150 Max	±1.5
NCS199A3R	200	±150 Max	±1.5

Table 4: NCS213R Customer Evaluation Board (PCB) Bill of Materials (BOM)

Designator	Quantity	Description	Value	Tolerance	Footprint	Manufacturer	Manufacturer Part Number	Substitution Allowed	Lead Free
C1, C2	2	Bypass capacitors	0.1 µF	20%	0805	KEMET	C0805C104K3 RACTU	Yes	Yes
R1	1	Shunt Resistor	1 mΩ	1 %	0805	Vishay	WSLP12061L0 00FEA	Yes	Yes
U1	1	Device	N/A	N/A	SC70-6	ON Semiconductor	NCS213R	No	Yes
TP1	6	Test Point	N/A	N/A	Contact	Keystone Electronics	TP-5016	Yes	Yes

The NCS213R Customer Evaluation Board is orderable as: NCS213RSQTGEVB.