Ed Mullins

TI Precision Designs: Reference Design
50 mA-20 A, Single-Supply, Low-Side or High-Side, Current Sensing Solution

TEXAS INSTRUMENTS

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Circuit Description

This single-supply, low-side or high-side, current sensing solution can accurately detect load currents from 50 mA to 20 A. The linear range of the output is from 0 V to 5 V. A unique yet simple gain switching network is implemented in order to accurately measure the load current across this wide dynamic range.

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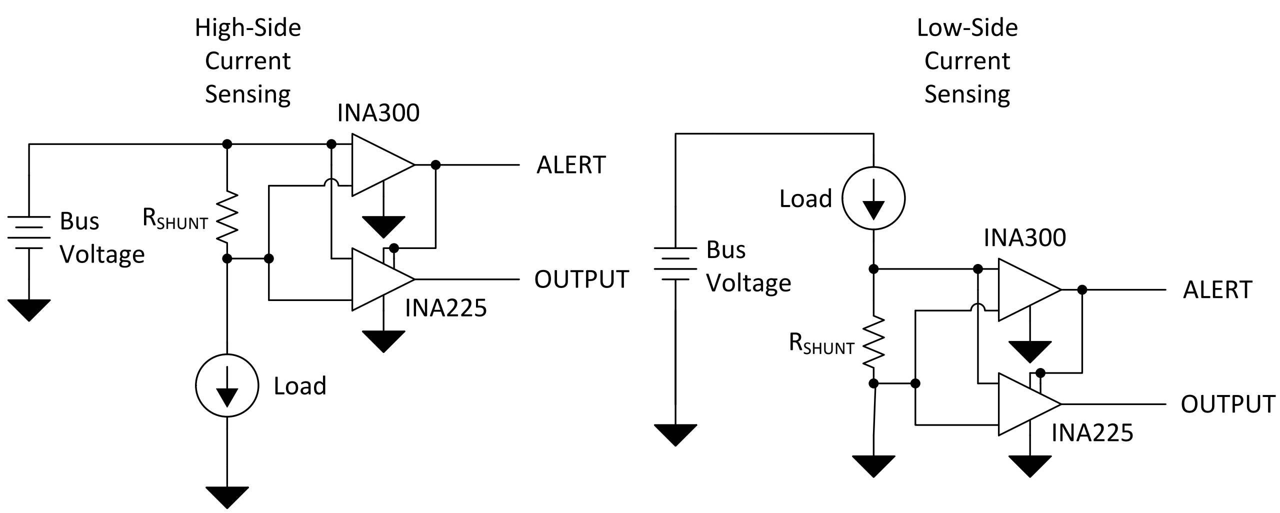

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1 Design Summary

The design requirements are as follows:

- Bus Voltage: 0 to 36V
- Load Current: 50mA to 20A
- Operate from a single 5V power supply
- Maximum Shunt Voltage: ≤200mV

Two unique current sensing devices are selected to implement this design. The INA225 is a precision current shunt monitor with pin selectable gain. The INA300 is a current sensing comparator which can be used to switch the gain of the INA225 to increase the dynamic range of the design. The design goals and simulated performance are summarized in Table 1. Figure 1 depicts the simulated transfer function of the design.

Table 1: Comparison of Design Goals and Simulated Performance

	Goal	Simulated
Minimum Detectable Current	50mA	25mA
Maximum Detectable Current	20A	20A

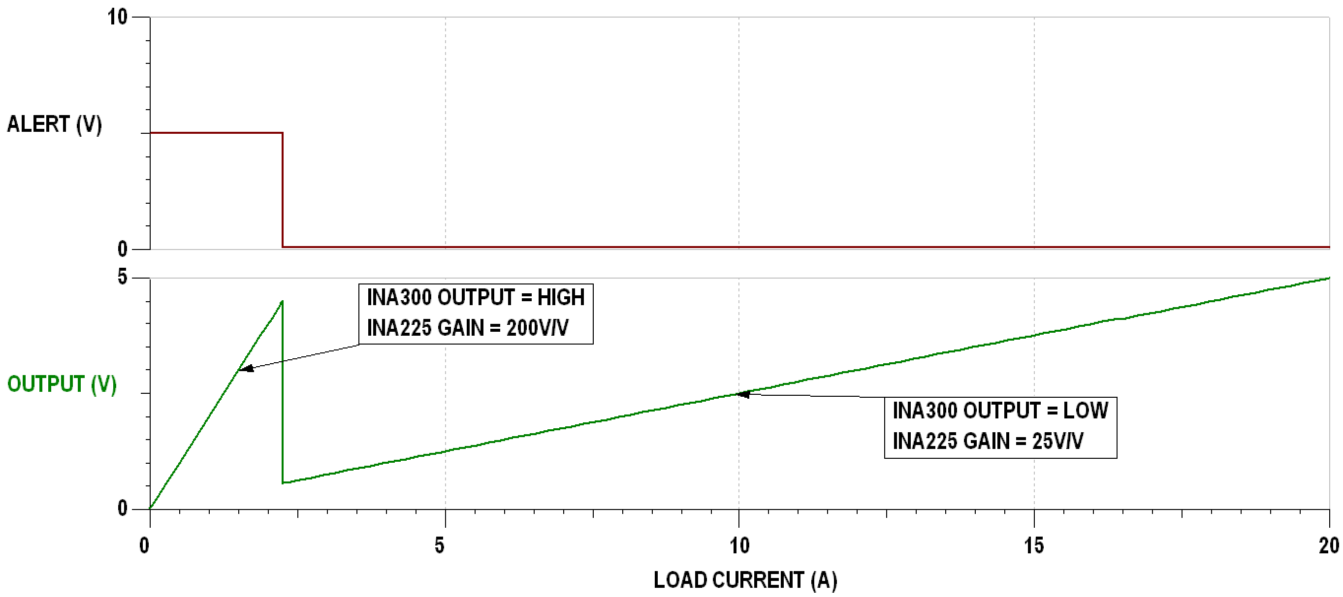

Figure 1: Simulated Transfer Function

2 Theory of Operation

2.1 Low-Side or High-Side Current Sensing

Accurately measuring current is required in systems when any of the following system attributes must be considered by a designer:

- Circuit Protection
- Fault Detection
- Power Efficiency and Control
- Product Safety

The most commonly encountered method to measure current is to place a small resistor in series with the load and measuring the voltage drop developed across the resistor. Commonly such a resistor is referred to as a "shunt resistor" or R_{SHUNT}. Figure 2 illustrates this concept.

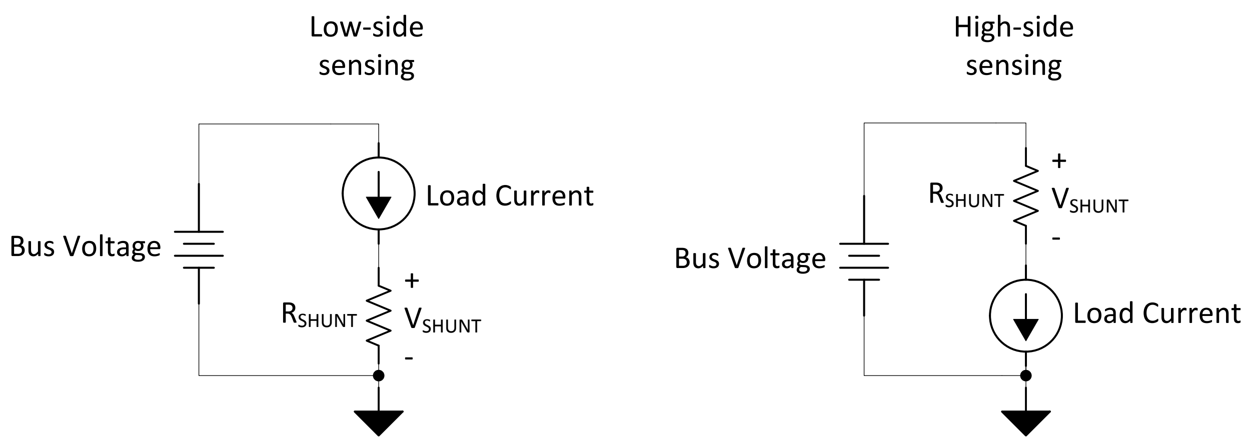

Figure 2: Current Sensing using a Shunt Resistor

There are two circuits illustrated in Figure (2). The circuit on the left hand side illustrates a circuit wherein R_{SHUNT} is connected between the load and ground. The type of connection is referred to as "low-side sensing". The circuit on the right hand side illustrates a circuit wherein R_{SHUNT} is connected between the bus voltage and the load. This type of connection is referred to as "high-side sensing". In either circuit configuration the current can be measured accurately, but there are important distinctions that a system designer must consider when deciding which configuration will work best in a given application. Table (2) shows a comparison between each configuration in terms of their unique features.

Table 2: Comparison of Features

	Low-side Sensing	High-side sensing
Can be used to measure current accurately	Yes	Yes
Can detect load shorts	No	Yes
Requires high common mode rejection amplifier	Yes/No	Yes
Poor grounding can result in measurement error	Yes	No
Low cost	Yes	Yes

2.1.1 Fault Detection

The ability to detect a short from the load to ground is an important differentiation between low-side and high-side sensing. When using low-side sensing should a short occur between the system load and ground the current that flows from the bus voltage source to ground (via the short) and will not flow through the shunt resistor and therefore the fault will not be detected. This short circuit could be low-level or moderate leakage or it could a hard failure representing some catastrophic event. In a high-side sensing configuration, should a similar short or failure occur, the current passes through the shunt resistor and is easily detectable. Figure (3) illustrates this concept. For circuits where system protection or user protection is required high-side sensing is recommended.

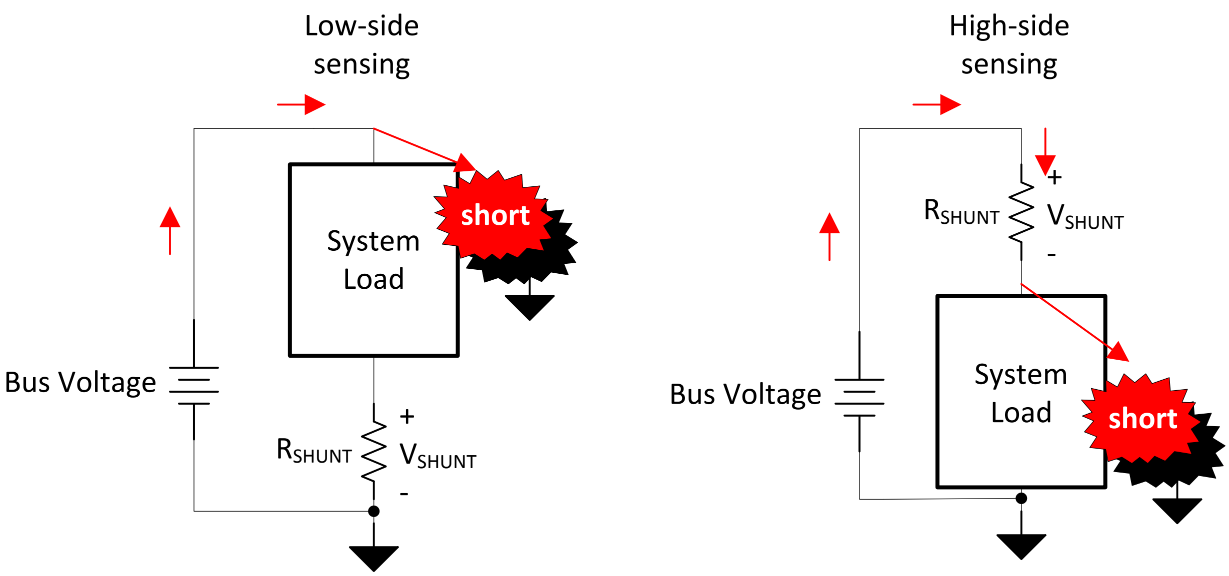

Figure 3: Fault Sensing using High-side Current Sensing

2.1.2 Common Mode Rejection Ratio

Common mode rejection ratio describes an amplifiers ability to reject signals that are common to both inputs. Common mode rejection is therefore an important amplifier parameter when attempting to measure small differential voltages in the presence of large common mode voltages. The voltage developed across the shunt resistor provides the differential input to an amplifier and it is this voltage that is intended to be accurately measured. When configured in a low-side current sensing solution the common mode voltage applied to the amplifier is essentially zero and in many cases can be ignored. This allows the designer to choose an amplifier that may not have very high common mode rejection ratio, and thus in some ways allows for a simpler design with fewer error sources to consider. When striving for maximum performance, an analysis which includes the effects of the amplifier common mode rejection (even in low-side configurations) is recommended. When configured in a high-side current sensing solution the common mode voltage is equal to the bus voltage. This requires that the bus voltage be rejected by the amplifier and therefore always requires an amplifier with high common mode rejection.

2.1.3 Low-side Sensing and Poor Grounding

Mentioned in Table (2), some low-side sensing configurations are susceptible to poor PCB layout, wiring issues and grounding issues. Figure (4) illustrates a simple low-side current sense circuit using only an operational amplifier to monitor the voltage developed across a shunt resistor. This circuit has a single-ended input and is susceptible to PCB trace and wiring resistance, ground bounce and noisy grounds. Notice that any resistance in series with the current shunt will create a voltage drop due to the load current flowing. Commonly this additional resistance in series with the shunt resistor is due to PCB trace resistance and or wiring resistance. This additional voltage drop across the undesired PCB trace or wiring resistance will add to the input signal developed only across the shunt resistor and introduce an error. This type of error is most significant at high currents and will vary widely over temperature due to the temperature coefficient of the resistance of the copper PCB trace, copper wiring or poor grounding.

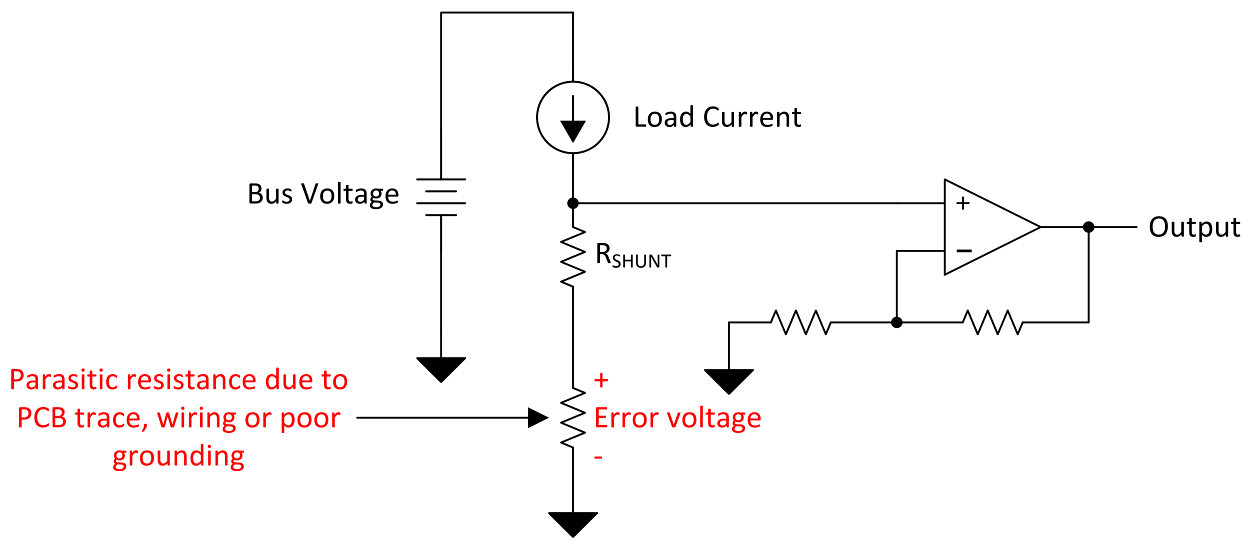

Figure 4: Errors Associated with Single-ended, Low-side Sensing

The solution to these problems is quite simple. Rather than using the single-ended type of amplifier circuit shown in Figure (4), use instead a current shunt monitor with differential inputs and rely upon the common mode rejection ratio to eliminate the errors associated with the PCB trace or wiring resistance and ground noise. Figure (5) illustrates this concept.

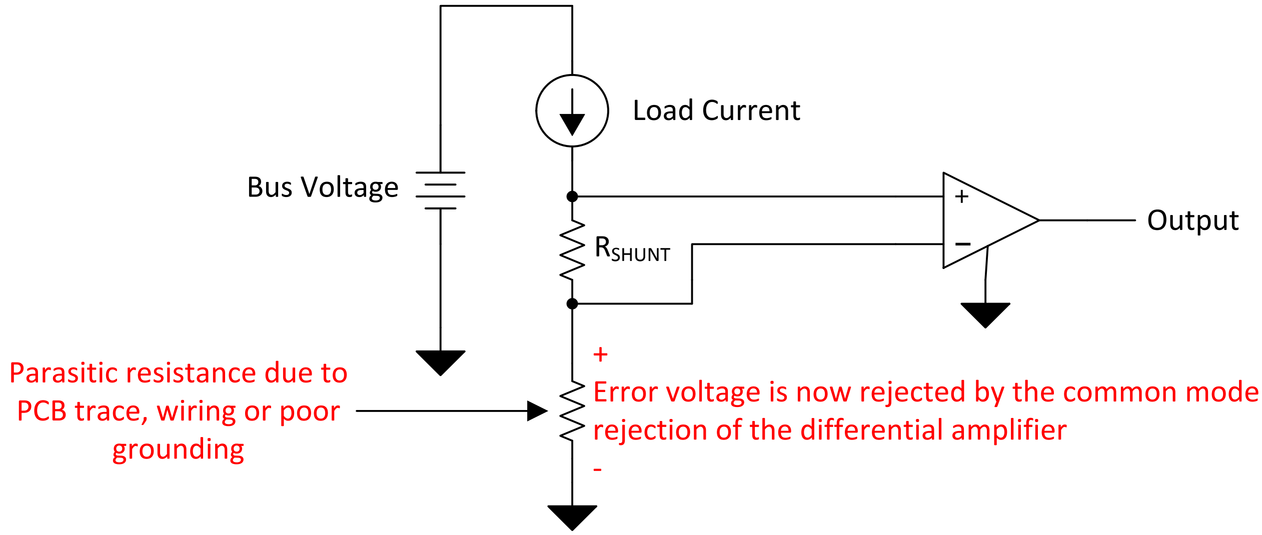

Figure 5: Errors are Eliminated by the Current Shunt Monitor in a Low-side Sensing Solution

2.2 Choosing the Shunt Resistor

The motivation to use a current shunt monitor for sensing the voltage drop across a shunt resistor is based upon the desire for accuracy and low system cost. The typical current shunt monitor will have low input offset voltage, low input offset voltage drift with temperature and high common mode rejection ratio. These error sources are most significant at low load currents (low input voltages). At high currents the gain error of the amplifier and shunt resistor tolerance also contributes to errors in the measurement. Minimizing these errors allows the use of increasingly smaller shunt resistors, thus reducing power loss in the shunt resistor as well as the size and cost of the shunt resistor. The desired current range for this application is given as 50 mA to 20A. This is a very wide range and consideration to the minimum current value and maximum current value is required.

2.2.1 Error Analysis at the Minimum Current Value

Consider a current shunt monitor that has an initial input offset voltage maximum of ±150µV and a minimum common mode rejection of 95dB. For either low-side or high-side sensing we must analyze the effect of these two error sources upon the ability to monitor small levels of shunt current. Before a proper worst case error analysis can be performed the details and conditions surrounding the device specifications of offset and common mode rejection must be taken into account. Such conditions are listed in the current shunt monitor device specification. Of particular interest to note are the conditions under which input offset voltage and common mode rejection are given in the data sheet. For this example it will be given that the conditions under which the current shunt monitor is specified are:

V_S = 5 V

Bus Voltage = 12 V

These two conditions are important as any deviation from them in the actual current sensing solution must be considered and properly calculated. For the following examples it is assumed that in the application the V_S is 5 V. This will minimize errors due to power supply voltage effects from the power supply rejection of the amplifier as the amplifier used in this design has its offset voltage specified at a V_S equal to 5V.

2.2.1.1 Low-side and High-side Sensing Minimum Current Error Analysis

In a low-side sensing configuration the common mode voltage at the current shunt monitor input is zero. But since the current shunt monitor is specified with a Bus Voltage of 12 V, this difference between device specification conditions and circuit application conditions must be considered. In this case there will be an effective -12 V common mode voltage "seen" by the current shunt monitor. To understand the impact from this -12 V common mode voltage a calculation of the input referred error must be made. Equation (1) illustrates this calculation.

$$Input\,error\,due\,to\,common\,mode\,effects = \left|\frac{Application_{CMV} - Specified_{CMV}}{CMRR}\right| \quad (1)$$

Where:

Application$_{CMV}$ is the common mode voltage in the application…for low-side sensing this is zero, for high-side sensing this is equal to the Bus Voltage

Specified$_{CMV}$ is the common mode voltage at which the devices offset volatge is specified (refer to the device data sheet)

CMRR is the minimum common mode rejection ratio given in the current shunt monitor device specification

Example:

$$Input\,error\,due\,to\,common\,mode\,effects = \left|\frac{0V - 12V}{95dB}\right| = \left|\frac{-12V}{56,234}\right| = 213\mu V \quad (2)$$

This error due to the common mode effect is an input referred voltage error, much like the initial device input offset voltage. Combining the two error terms (common mode error and initial input offset) is required to determine the total error from the current shunt monitor. While it may be tempting to linearly add the two error terms together to determine a worst case value, in reality these two errors are uncorrelated to one another and therefore can be added as the square root of the sum of the squares. Equation (3) illustrates this combination of error terms.

$$Total\,input\,referred\,error = \sqrt{Vosi^2 + CME^2} \quad (3)$$

Where:
Vosi is the maximum initial input referred offset given in the current shunt monitor specification

CME is the input referred error due to common mode effects as determined previously

Example:

$$Total\,input\,referred\,error = \sqrt{150\mu V^2 + 213\mu V^2} = 261\mu V \quad (4)$$

This total input referred error is the uncertainty of the input voltage under zero input conditions. With the desire to monitor load currents as small as 50 mA a minimum value of shunt resistor can be determined by Equation (5):

$$Minimum\,value\,of\,\,shunt\,resistor = \frac{Total\,input\,referred\,error}{Minimum\,load\,current} \quad (5)$$

Example:

$$Minimum\,value\,of\,\,shunt\,resistor = \frac{261\mu V}{50mA} = 5.2m\Omega \quad (6)$$

What the example illustrates is that if a 5.2mΩ shunt resistor is selected an uncertainty of up to ±50mA will be present even when the load current is zero. Another way to think about this is to recognize that for the values used in the example, having an uncertainty of ±50mA will result in a 100% total measurement error for an ideal input current of 50 mA. Increasing the shunt resistor value will reduce the amount of uncertainty, and therefore result in reduced errors. Increasing the shunt resistor too much will result in overvoltage at the amplifier output as well and lead to increased power dissipation when the load current is at a maximum. Therefore the shunt resistor must lie within a range. Analysis for the case of high-side sensing is performed the same as for low-side sensing referenced above.

2.2.1.2 Low-side and high-side Sensing Maximum Current Analysis

The maximum load current to be sensed should correspond to the maximum output voltage from the current shunt monitor. A current shunt monitor amplifier is configured in either a fixed gain or selectable gain. Choosing a device with a gain = 25V/V and a 5 V maximum output will require a maximum input voltage developed across the shunt resistor at the full load current of 200 mV. Determining the required shunt resistor value is performed by dividing the maximum shunt voltage required by the maximum load current.

Example:

$$Maximum\,value\,of\ shunt\,resistor = \frac{Maximum\,Output\,Voltage / Gain}{Maximum\,Load\,Current} = \frac{5V / 25V/V}{20A} = 10m\Omega \tag{7}$$

Equation (7) defines the maximum value for the shunt resistor, beyond which saturation of the output voltage would occur. A range now has been established for the shunt resistor value bounded on the low end by the desired minimum detectable current with 100% error and on the high end by the maximum output voltage swing. Please note that the maximum output voltage swing is a function of power supply voltage and the amplifier output swing specification in the device datasheet.

$$5.2m\Omega \le R_{SHUNT} \le 10m\Omega \tag{8}$$

The power dissipation from the load current flowing through the shunt resistor is determined as shown in Equation (9):

$$Maximum\ power\ dissipated\ by\ shunt\ resistor = Maximum\,Load\,Current^2 \times Shunt\ Resistor \tag{9}$$

Example:

$$Maximum\ power\ dissipated\ by\ shunt\ resistor = 20A^2 \times 10m\Omega = 4W \tag{10}$$

It may be tempting to reduce the shunt resistor value from the maximum of 10 mΩ in an effort to reduce power dissipated, and this certainly can be performed, but it will come at the expense of the low current accuracy.

Example:

Reducing the shunt resistor value from 10 mΩ to 1 mΩ will reduce the power dissipation by the same ratio, to 0.4 W. This will certainly allow for a smaller shunt resistor; however the accuracy on the low end of the load current range will be degraded. The following example illustrates the amount of error in the current measurement as a function of reducing the shunt resistor.

Example:

$$Minimum\,current\,to\,be\,detected = \frac{Total\,input\,referred\,error}{Shut\,Resistor} = \frac{261\mu V}{1m\Omega} = 261mA \qquad (11)$$

Notice that this is also a factor of 10 times larger than the previously calculated value. There is always a tradeoff to be made in terms of low current accuracy and power dissipation at full scale. Selecting a current shunt monitor with minimal errors will allow for the most effective tradeoff, and therefore the most optimum choice of shunt resistor size and cost. All of the above analysis and examples are applicable to both low-side sensing and high-side sensing configurations.

3 Component Selection

The most critical passive component with regards to performance and accuracy is the shunt resistor. Factors such as initial tolerance, temperature coefficient, power rating, size and cost are all important parameters and must be taken under consideration when choosing the shunt resistor. In this design a CSSH2728 (Stackpole Electronics, Inc.), 10mΩ, 4W, 0.5% resistor is assumed. This resistor offers high initial accuracy, adequate power handling capability, a small surface mount footprint, and low temperature drift (15ppm/C). Lower performance options within this same resistor family are also available at the time of this publication which allows an additional flexibility between performance and price.

3.1 Amplifier

Two amplifiers are used in this design.

The INA225 is a high-side or low-side current shunt monitor with pin selectable gain.

The INA300 is a high-side or low-side current shunt comparator with open drain output. The open drain output is used to control the gain selection pins on the INA225.

Because both amplifiers can be used over a common mode voltage range of 0 V to 36 V a high-side or low-side configuration can be utilized with similar performance. Basic circuit operation is described for the low-side configuration shown in Figure (6).

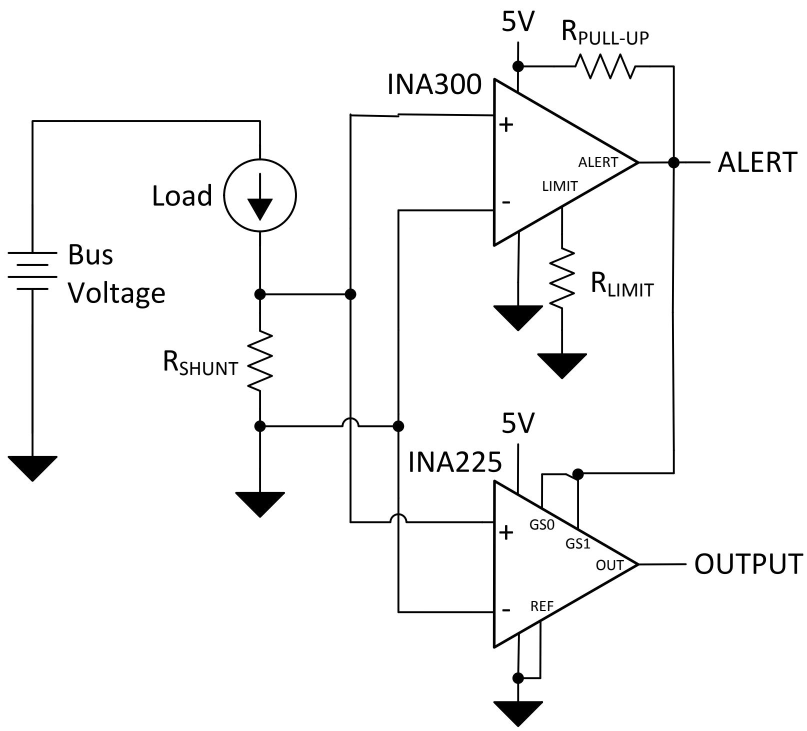

Figure 6: Basic Operation of the Low-side Sensing Solution

Both inputs from the INA225 and INA300 are used to sense directly across the shunt resistor. The basic operation is described as the INA225 is configured in its maximum gain (200V/V) for small values of load current and when the current becomes large enough the INA225 gain is switched to its lowest available setting (25V/V). This gain switching is achieved by connecting the alert output (open drain) of the INA300 to both GS0 and GS1 (gain selection pins) on the INA225. At very small currents the INA300 output is high and thus drives the INA225 gain select pins high, resulting in a gain of 200V/V for the INA225. When the load current increases beyond a threshold level, the alert output of the INA300 pulls the gain select pins of the INA225 low, resulting in a gain of 25V/V, thereby extending the range of current detection.

Setting the threshold at which the INA300 will trip is determined by the voltage at the LIMIT pin of the INA300. This voltage can either be applied directly from a DAC output or it can be created by placing the appropriate sized resistor from the LIMIT pin to ground. Placing a resistor between the LIMIT pin and ground creates a voltage (V_{LIMIT}) given by Equation (12):

$$V_{LIMIT} = 20\mu A \times R_{LIMIT} \tag{12}$$

There is a one to one relationship between V_{LIMIT} and the threshold voltage at which the INA300 will trip, as such:

$$V_{THRESHOLD} = V_{LIMIT} \tag{13}$$

The value at which the INA300 trips (and switches the gain of the INA225) should occur before the output of the INA225 reaches its maximum limit. When powered from a 5V power supply, the maximum value of the output voltage of the INA225 is given in the data sheet as 4.8V. Using a 5 V power supply the desired switch point would occur before the INA225 output reaches 4.8 V. Considering the condition where the input current is small and INA225 gain is therefore large (200V/V) requires the input threshold voltage to occur at a maximum value of 4.8V divided by the gain of the INA225. This results in a maximum threshold voltage of 24mV. Choosing a limit resistor value of 1.13kΩ results in the limit voltage of 22.6mV. Using a 10mΩ shunt resistor results in a threshold load current value of 2.26A. What this results in is when the load current is less than 2.26A the INA225 is configured in a gain of 200 V/V and when the load current exceeds 2.26 A the INA225 is configured in a gain of 25 V/V.

4 Simulation

Simulation models for both the INA225 and INA300 are available at www.ti.com. These models can be used to simulate the operation of the described circuit.

4.1 Transfer Function

Figure (7) illustrates the transfer functions for both the Alert output from the INA300 and the analog output from the INA225 as a function of load current. The INA300 trip point has been set at 2.26 A as previously described.

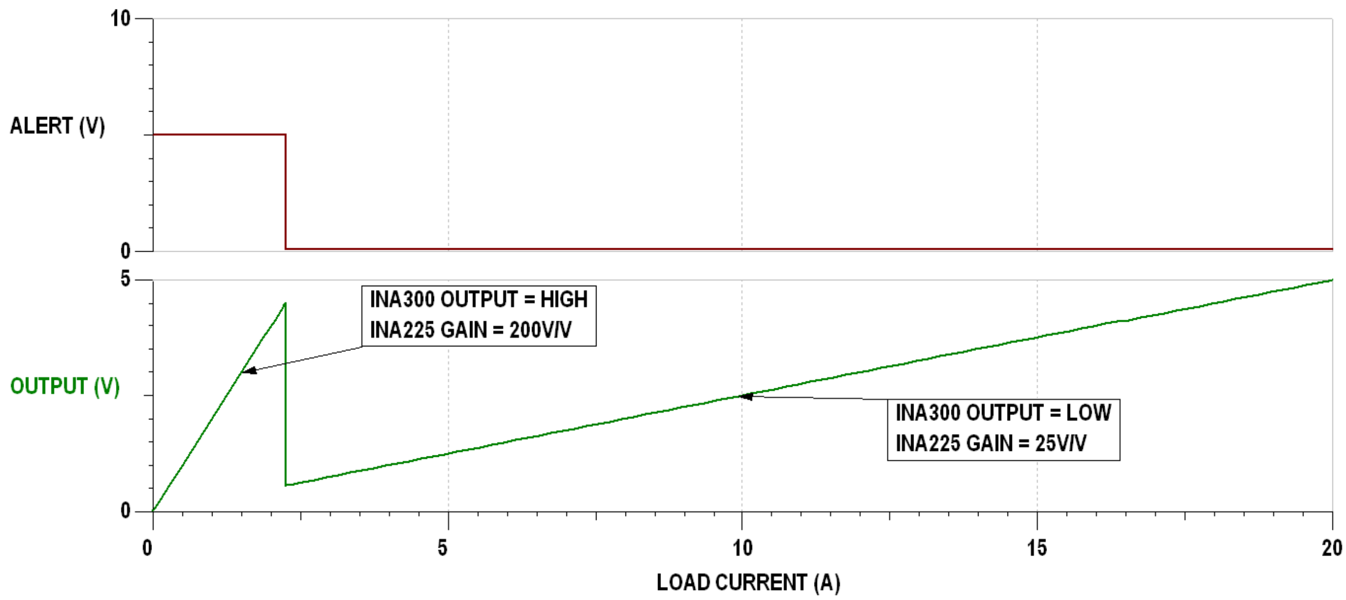

Figure 7: Transfer Function

4.2 *The Impact of the Hysteresis setting on the INA300*

The INA300 is a current shunt comparator that has pin selectable hysteresis. Hysteresis is required to prevent multiple or false comparator changes of state due to the presence of noise in the system. As an example of how the amount of hysteresis relates to the transfer function please refer to Figure (8). Notice that as the load current starts to increase from some very small value (below the trip point of 2.26 A) the output voltage increases with a gain of 200 V/V until the threshold voltage is reached. This corresponds to an input referred trip point of 22.6 mV as previously described. The INA225 gain is then reduced to 25 V/V and the output continues to increase with increasing load current. As the load current begins to decrease it will eventually decrease to the value of the trip point, however due to the amount of hysteresis set by the INA300 the trip point occurs at a slightly lower load current level. In the simulation case used to create Figure (8), the INA300 was configured to have 4 mV of hysteresis. This was achieved by connecting the Hysteresis pin on the INA300 to ground.

Since the hysteresis refers to the amount of change of threshold voltage at the INA300 input, this hysteresis value can be converted to the amount of hysteresis in terms of load current by dividing by the value of the shunt resistor value.

$$LOAD\,CURRENT_{HYSTERESIS} = \frac{Hysteresis_{INA300}}{R_{SHUNT}} \tag{14}$$

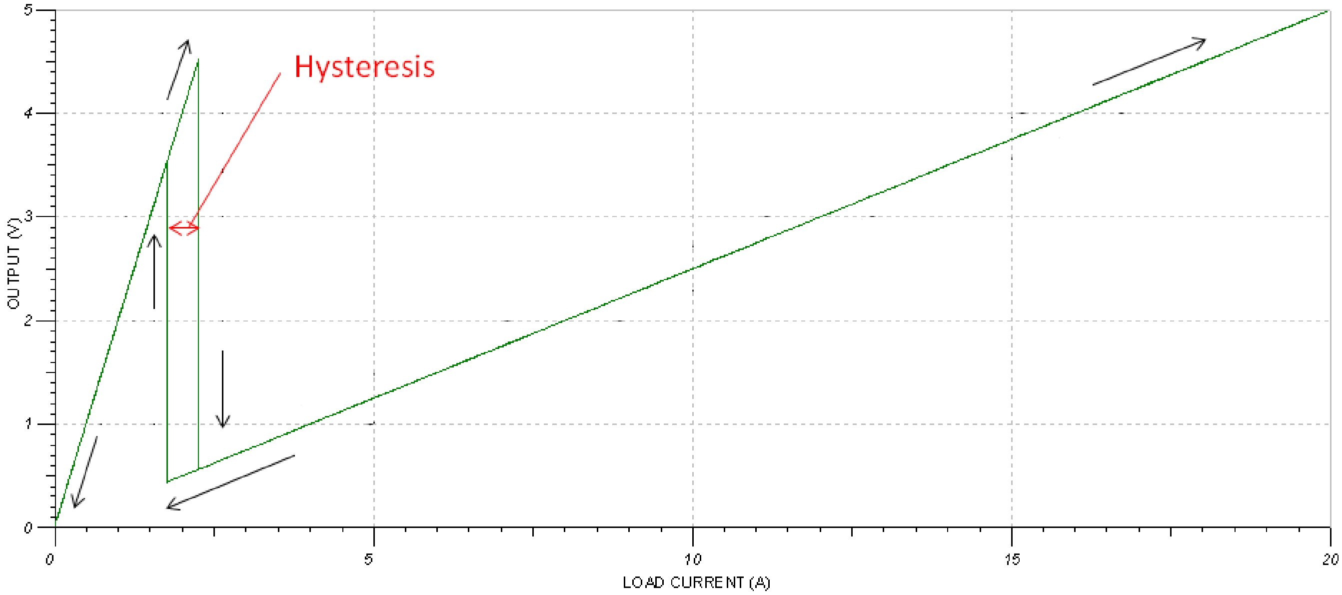

Figure 8: Hysteresis

4.3 The Complete Circuit

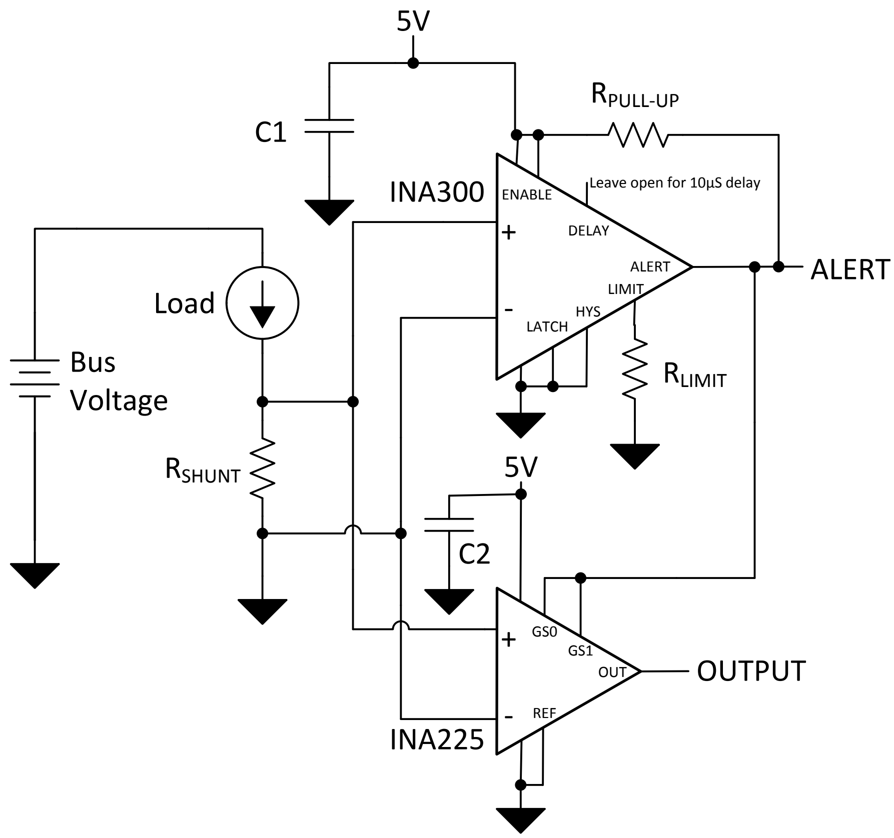

Figure 9: Complete Circuit for Low-side Sensing

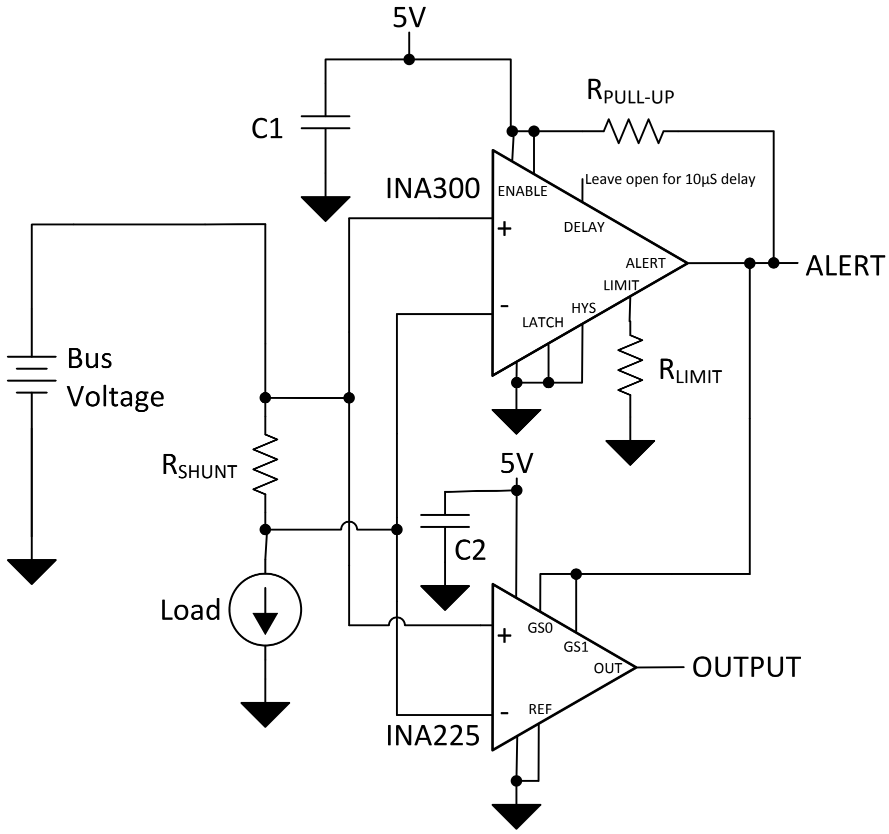

Figure 10: Complete Circuit for High-side Sensing

5 Measuring "Zero" Load Current

Other considerations which can impact performance not discussed in the above analysis are the finite output voltage swing to ground limitations of the INA225. For example when there is zero load current the output of the INA225 cannot swing all the way to ground if it is configured in a single supply configuration shown in either Figure (9) or Figure (10). Please refer to the limitations described in the INA225 specification. As an example, if the load current is zero and all other error sources are also zero, the output may only swing as low as 50 mV due to the output swing to ground limitation. When in a gain of 200 V/V it would appear as if there was in input voltage given by Equation (15):

$$\frac{Output\ swing}{Gain} = \frac{50mV}{200V/V} = 250\mu V \tag{15}$$

This 250µV of input error can be related to an error in load current given by Equation (16):

$$Load\ current\ error = \frac{input\ error}{R_{SHUNT}} = \frac{250\mu V}{10m\Omega} = 25mA \tag{16}$$

If measuring zero load current is desired it will be required to add a low output impedance voltage input to the INA225 REF pin. Please refer to the INA225 data sheet for additional information. Other sources sources of error can arise from specific PCB layout issues that alter the value of the shunt resistance or issues that can arise from self-heating of the shunt resistor if exposed to prolonged periods of excessive power dissipation.

6 Maximum Output Voltage Limitations and Power Supply Tolerance

The output voltage of the INA225 is specified to swing to within 200 mV of the power supply voltage. This implies that with a power supply voltage of 5 V, the maximum output that the INA225 can achieve is 4.8V. Assuming a 20 A load current and INA225 gain of 25 V/V the maximum value for the shunt resistor must be reduced to 9.6 mΩ. Further impacting the maximum value for the INA225 output is the tolerance for the power supply voltage. For example if the power supply voltage is specified as 5 V with a 5% tolerance, the minimum supply voltage is then 4.75V…this in turn will limit the maximum output voltage of the INA225 to 4.55 V. Reducing the shunt resistor to a maximum value of 9.1 mΩ would be required to ensure a full scale input of 20 A can be accommodated at the INA225 output. The alternative is to leave the shunt resistor at the 10 mΩ value and have a maximum measureable load current, under the assumption of a 5% power supply tolerance, of 18.2A

7 Verification

This design was constructed and verified using the INA225EVM combined with the INA300EVM.

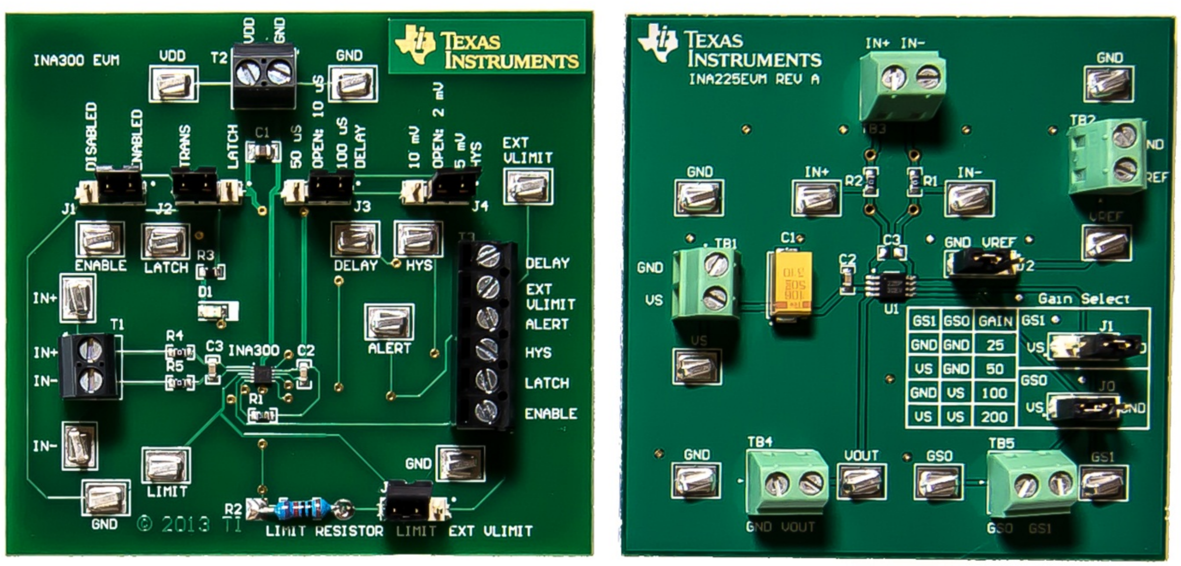

Figure 11: INA225 and INA300 Evaluation Modules

8 About the Author

Ed Mullins has more than 20 years of experience with Texas Instruments with a background in Analog IC Design and Applications Engineering.

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TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

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