TEXAS INSTRUMENTS

INA250A1, INA250A2, INA250A3, INA250A4

SBOS511B – APRIL 2015 – REVISED DECEMBER 2015

INA250 36-V, Low- or High-Side, Bidirectional, Zero-Drift Current-Shunt Monitor with Precision Integrated Shunt Resistor

1 Features

- Precision Integrated Shunt Resistor:
  - Shunt Resistor: 2 mΩ
  - Shunt Resistor Tolerance: 0.1% (Max)
  - 15 A Continuous from –40°C to 85°C
  - 0°C to 125°C Temperature Coefficient: 10 ppm/°C
- High Accuracy:
  - Gain Error (Shunt and Amplifier): 0.3% (Max)
  - Offset Current: 50 mA (Max, INA250A2)
- Four Available Gains:
  - INA250A1: 200 mV/A
  - INA250A2: 500 mV/A
  - INA250A3: 800 mV/A
  - INA250A4: 2 V/A
- Wide Common-Mode Range: –0.1 V to 36 V
- Specified Operating Temperature: –40°C to 125°C

2 Applications

- Test Equipment
- Power Supplies
- Servers
- Telecom Equipment
- Automotive
- Solar Inverters
- Power Management

3 Description

The INA250 is a voltage-output, current-sensing amplifier family that integrates an internal shunt resistor to enable high-accuracy current measurements at common-mode voltages that can vary from 0 V to 36 V, independent of the supply voltage. The device is a bidirectional, low- or high-side current-shunt monitor that allows an external reference to be used to measure current flowing in both directions through the internal current-sensing resistor sensor. The integration of the precision current-sensing resistor provides calibration equivalent measurement accuracy with ultra-low temperature drift performance and ensures an optimized Kelvin layout for the sensing resistor is always obtained.

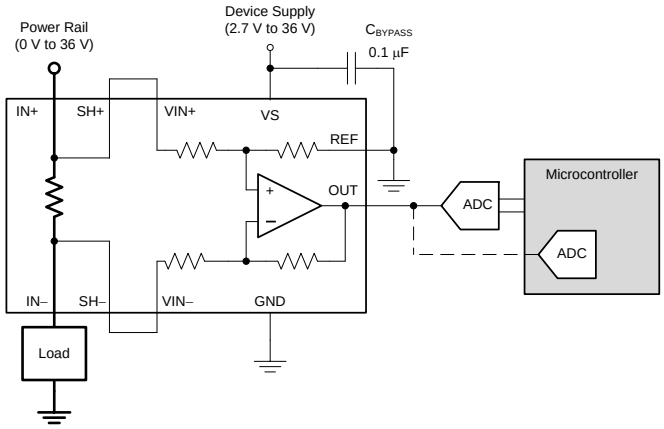
The INA250 family is available in four output voltage scales: 200 mV/A, 500 mV/A, 800 mV/A, and 2 V/A. This device is fully tested and specified for continuous currents up to 10 amps at the maximum temperature of 125°C. The INA250 operates from a single 2.7-V to 36-V supply and draws a maximum of 300 µA of supply current. All INA250 gain versions are specified over the extended operating temperature range (–40°C to 125°C), and are available in a TSSOP-16 package.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
INA250A1	TSSOP (16)	5.00 mm × 4.40 mm
INA250A2		
INA250A3		
INA250A4		

(1) For all available packages, see the orderable addendum at the end of the datasheet.

Simplified Schematic



An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.

Table of Contents

1 Features ... 1
2 Applications ... 1
3 Description ... 1
4 Revision History ... 2
5 Pin Configuration and Functions ... 3
6 Specifications ... 4
6.1 Absolute Maximum Ratings ... 4
6.2 ESD Ratings ... 4
6.3 Recommended Operating Conditions ... 4
6.4 Thermal Information ... 4
6.5 Electrical Characteristics ... 5
6.6 Typical Characteristics ... 7
7 Detailed Description ... 12
7.1 Overview ... 12
7.2 Functional Block Diagram ... 12
7.3 Feature Description ... 12
7.4 Device Functional Modes ... 15
8 Applications and Implementation ... 19
8.1 Application Information ... 19
8.2 Typical Applications ... 19
9 Power Supply Recommendations ... 23
10 Layout ... 24
10.1 Layout Guidelines ... 24
10.2 Layout Examples ... 24
11 Device and Documentation Support ... 26
11.1 Documentation Support ... 26
11.2 Related Links ... 26
11.3 Community Resources ... 26
11.4 Trademarks ... 26
11.5 Electrostatic Discharge Caution ... 26
11.6 Glossary ... 26
12 Mechanical, Packaging, and Orderable Information ... 26

4 Revision History

Changes from Revision A (May 2015) to Revision B **Page**

- Released INA250A1, INA250A3, and INA250A4 to production ... 1
- Added TI Design ... 1
- Added parameters for INA250A1, INA250A3, and INA250A4 to *Electrical Characteristics* table ... 5
- Added ± to specifications for the *Shunt short time overload*, *Shunt thermal shock*, *Shunt resistance to solder heat*, *Shunt high temperature exposure*, and *Shunt cold temperature storage* parameters of *Electrical Characteristics* table ... 5
- Added curves for INA250A1, INA250A3, and INA250A4 to *Typical Characteristics* section ... 7
- Added *Amplifier Operation* section ... 15
- Added *Community Resources* section ... 26

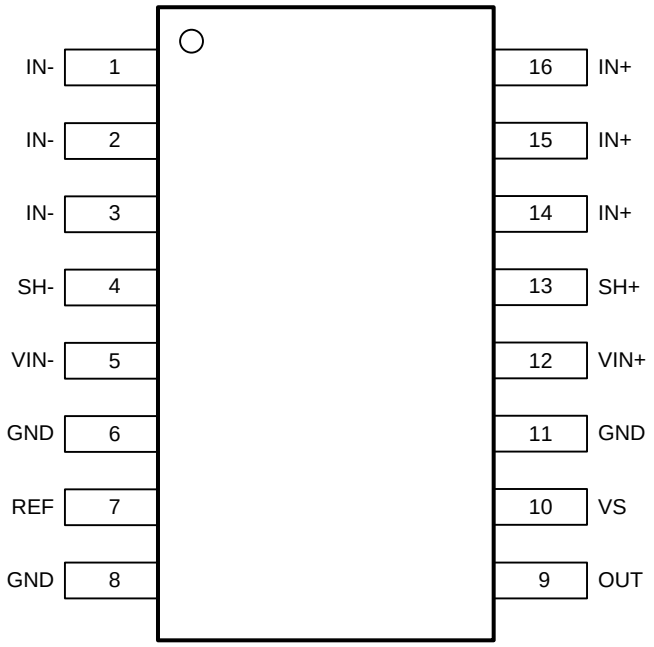
Changes from Original (April 2015) to Revision A **Page**

- INA250A2 released to production ... 1

Copyright © 2015, Texas Instruments Incorporated

5 Pin Configuration and Functions

PW Package
16-Pin TSSOP
Top View



Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
GND	6, 8, 11	Analog	Ground
IN–	1, 2, 3	Analog input	Connect to load
IN+	14, 15, 16	Analog input	Connect to supply
OUT	9	Analog output	Output voltage
REF	7	Analog input	Reference voltage, 0 V to VS (up to 18 V)
SH–	4	Analog output	Kelvin connection to internal shunt. Connect to VIN– if no filtering is needed. See Figure 33 for filter recommendations.
SH+	13	Analog output	Kelvin connection to internal shunt. Connect to VIN+ if no filtering is needed. See Figure 33 for filter recommendations.
VIN–	5	Analog input	Voltage input from load side of shunt resistor.
VIN+	12	Analog input	Voltage input from supply side of shunt resistor.
VS	10	Analog	Device power supply, 2.7 V to 36 V

Copyright © 2015, Texas Instruments Incorporated

6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

		MIN	MAX	UNIT
Supply voltage (VS)			40	V
Analog input current	Continuous current		±15	A
Analog inputs (IN+, IN–)	Common-mode	GND – 0.3	40	V
Analog inputs (VIN+, VIN–)	Common-mode	GND – 0.3	40	V
	Differential (V_{IN+}) – ($V_{IN–}$)	–40	40	
Analog inputs (REF)		GND – 0.3	VS + 0.3	V
Analog outputs (SH+, SH–)	Common-mode	GND – 0.3	40	V
Analog outputs (OUT)		GND – 0.3	(VS + 0.3) up to 18	V
Temperature	Operating, T_A	–55	150	°C
	Junction, T_J		150	
	Storage, T_{stg}	–65	150	

(1) Stresses above these ratings may cause permanent damage. Exposure to absolute maximum conditions for extended periods may degrade device reliability. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those specified is not implied.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001(1)	±2000	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101(2)	±1000	

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
(2) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

		MIN	NOM	MAX	UNIT
V_{CM}	Common-mode input voltage	0		36	V
VS	Operating supply voltage	2.7		36	V
T_A	Operating free-air temperature	–40		125	°C

6.4 Thermal Information

THERMAL METRIC(1)		INA250 PW (TSSOP) 16 PINS	UNIT
$R_{\theta JA}$	Junction-to-ambient thermal resistance	104.4	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	42.3	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	48.5	°C/W
ψ_{JT}	Junction-to-top characterization parameter	4.5	°C/W
ψ_{JB}	Junction-to-board characterization parameter	48	°C/W
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance	N/A	°C/W

(1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, SPRA953.

Copyright © 2015, Texas Instruments Incorporated

6.5 Electrical Characteristics

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
INPUT						
V_{CM}	Common-mode input range		–0.1		36	V
CMR	Common-mode rejection	INA250A1, V_{IN+} = 0 V to 36 V, T_A = –40°C to 125°C	94	102		dB
		INA250A2, V_{IN+} = 0 V to 36 V, T_A = –40°C to 125°C	97	110		
		INA250A3, V_{IN+} = 0 V to 36 V, T_A = –40°C to 125°C	106	114		
		INA250A4, V_{IN+} = 0 V to 36 V, T_A = –40°C to 125°C	108	118		
I_{OS}	Offset current, RTI(1)	INA250A1, I_{SENSE} = 0 A		±15	±100	mA
		INA250A2, I_{SENSE} = 0 A		±12.5	±50	
		INA250A3, I_{SENSE} = 0 A		±5	±30	
		INA250A4, I_{SENSE} = 0 A		±5	±20	
dI_{OS}/dT	RTI versus temperature	T_A = –40°C to 125°C		25	250	µA/°C
PSR		VS = 2.7 V to 36 V, T_A = –40°C to 125°C		±0.03	±1	mA/V
I_B	Input bias current	I_{B+}, I_{B-}, I_{SENSE} = 0 A		±28	±35	µA
V_{REF}	Reference input range(2)		0		(VS) up to 18	V
SHUNT RESISTOR(3)						
R_{SHUNT}	Shunt resistance (SH+ to SH–)	Equivalent resistance when used with onboard amplifier	1.998	2	2.002	mΩ
		Used as stand-alone resistor(4)	1.9	2	2.1	
	Package resistance	IN+ to IN–		4.5		mΩ
	Resistor temperature coefficient	T_A = –40°C to 125°C		15		ppm/°C
		T_A = –40°C to 0°C		50		
		T_A = 0°C to 125°C		10		
I_{SENSE}	Maximum continuous current(5)	T_A = –40°C to 85°C			±15	A
	Shunt short time overload	I_{SENSE} = 30 A for 5 seconds		±0.05%		
	Shunt thermal shock	–65°C to 150°C, 500 cycles		±0.1%		
	Shunt resistance to solder heat	260°C solder, 10 s		±0.1%		
	Shunt high temperature exposure	1000 hours, T_A = 150°C		±0.15%		
	Shunt cold temperature storage	24 hours, T_A = –65°C		±0.025%		

(1) RTI = referred-to-input.
(2) The supply voltage range maximum is 36 V, but the reference voltage cannot be higher than 18 V.
(3) See the *Integrated Shunt Resistor* section for additional information regarding the integrated current-sensing resistor.
(4) The internal shunt resistor is intended to be used with the internal amplifier and is not intended to be used as a stand-alone resistor. See the *Integrated Shunt Resistor* section for more information.
(5) See Figure 30 and the *Layout* section for additional information on the current derating and layout recommendations to improve the current handling capability of the device at higher temperatures.

Copyright © 2015, Texas Instruments Incorporated

Electrical Characteristics (continued)

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
OUTPUT						
G	Gain	INA250A1		200		mV/A
		INA250A2		500		
		INA250A3		800		
		INA250A4		2		V/A
	System gain error(6)	I_{SENSE} = –10 A to 10 A, T_A = 25°C		±0.05%	±0.3%	
		I_{SENSE} = –10 A to 10 A, T_A = –40°C to 125°C			±0.75%	
		T_A = –40°C to 125°C			45	ppm/°C
	Nonlinearity error	I_{SENSE} = 0.5 A to 10 A		±0.03%		
R_O	Output impedance			1.5		Ω
	Maximum capacitive load	No sustained oscillation		1		nF
VOLTAGE OUTPUT(7)						
	Swing to VS power-supply rail	R_L = 10 kΩ to GND		(VS) – 0.1	(VS) – 0.2	V
	Swing to GND	R_L = 10 kΩ to GND		(V_{GND}) + 25	(V_{GND}) + 50	mV
FREQUENCY RESPONSE						
BW	Bandwidth	INA250A1, C_L = 10 pF		50		kHz
		INA250A2, C_L = 10 pF		50		
		INA250A3, C_L = 10 pF		35		
		INA250A4, C_L = 10 pF		11		
SR	Slew rate	C_L = 10 pF		0.2		V/µs
NOISE, RTI(1)						
	Voltage noise density	INA250A1		51		nV/√Hz
		INA250A2		35		
		INA250A3		37		
		INA250A4		27		
POWER SUPPLY						
VS	Operating voltage range		2.7		36	V
I_Q	Quiescent current	T_A = –40°C to 125°C		200	300	µA
TEMPERATURE RANGE						
	Specified range		–40		125	°C

(6) System gain error includes amplifier gain error and the integrated sense resistor tolerance. System gain error does not include the stress related characteristics of the integrated sense resistor. These characteristics are described in the *Shunt Resistor* section of the *Electrical Characteristics* table.
(7) See *Typical Characteristics* curve, *Output Voltage Swing vs Output Current* (Figure 19).

Copyright © 2015, Texas Instruments Incorporated

6.6 Typical Characteristics

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

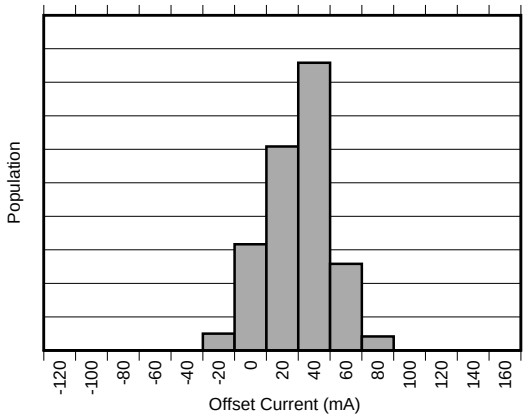


Figure 1. INA250A1 Input Offset Distribution

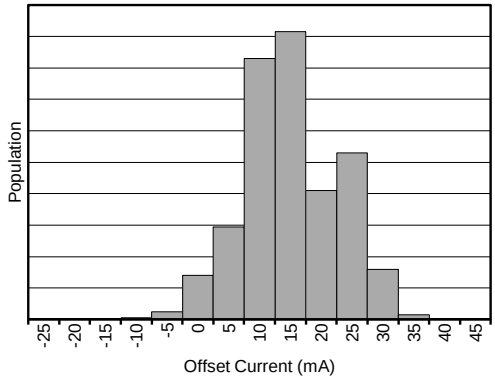


Figure 2. INA250A2 Input Offset Distribution

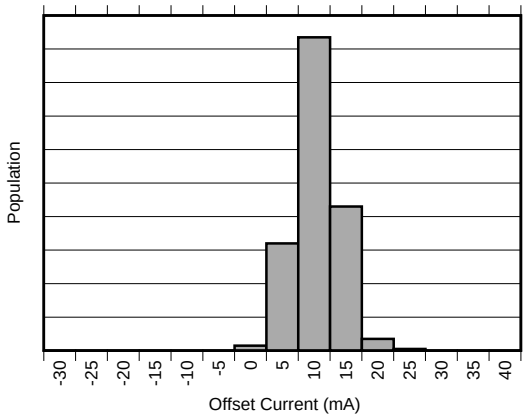


Figure 3. INA250A3 Input Offset Distribution

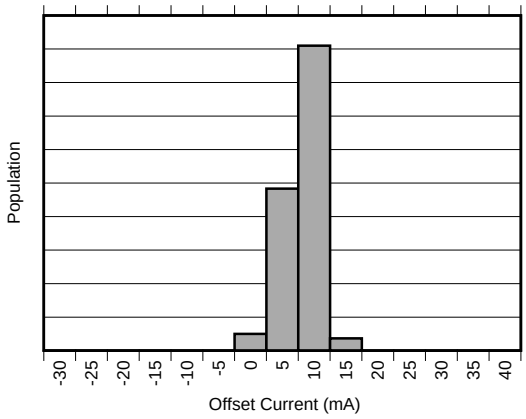


Figure 4. INA250A4 Input Offset Distribution

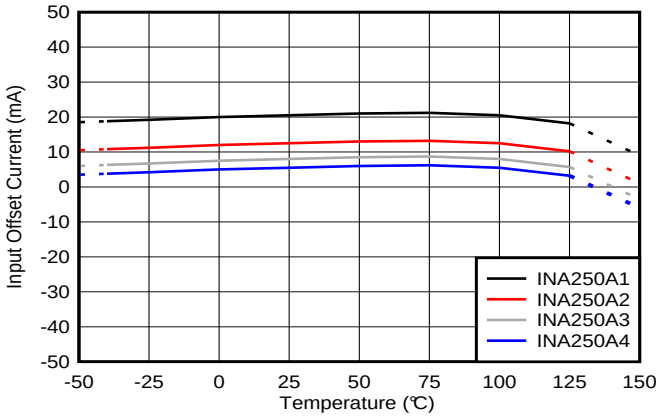


Figure 5. Input Offset vs Temperature

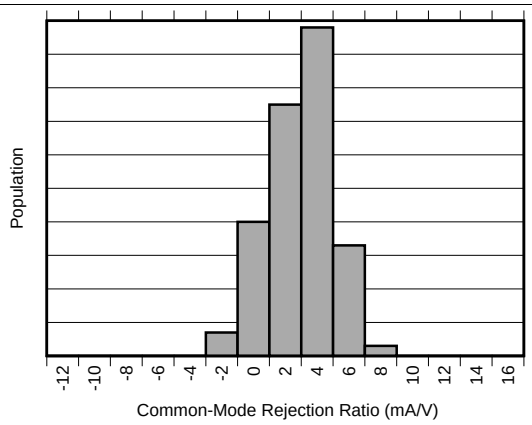


Figure 6. INA250A1 Common-Mode Rejection Ratio Distribution

Typical Characteristics (continued)

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

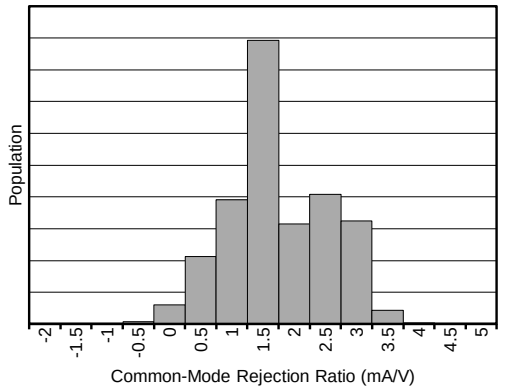


Figure 7. INA250A2 Common-Mode Rejection Ratio Distribution

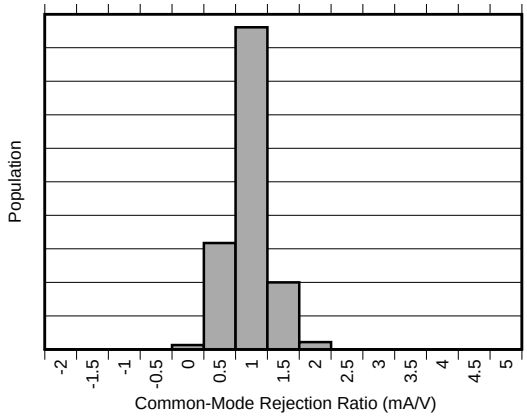


Figure 8. INA250A3 Common-Mode Rejection Ratio Distribution

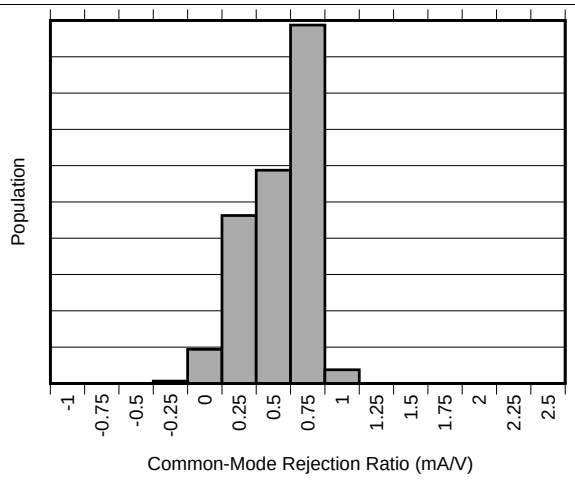


Figure 9. INA250A4 Common-Mode Rejection Ratio Distribution

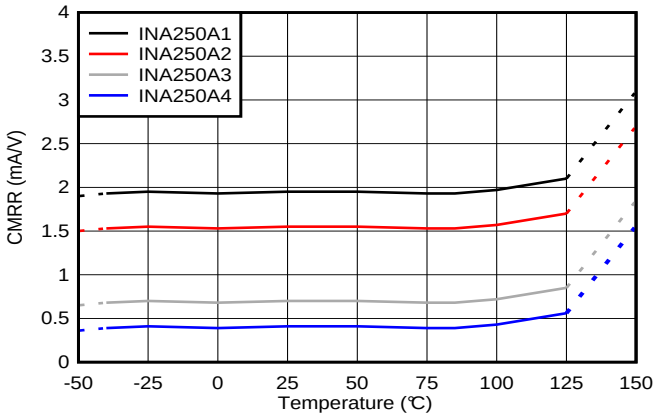


Figure 10. Common-Mode Rejection Ratio vs Temperature

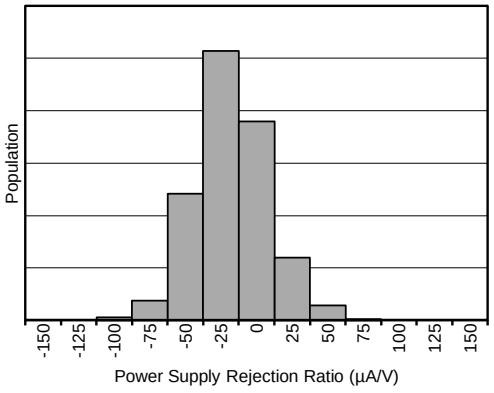


Figure 11. Power-Supply Rejection Ratio Distribution

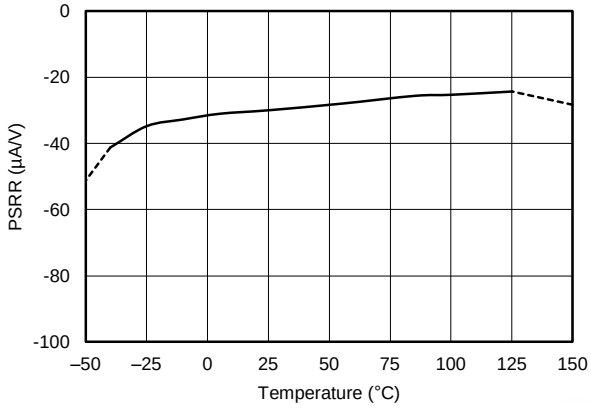


Figure 12. Power-Supply Rejection Ratio vs Temperature

Copyright © 2015, Texas Instruments Incorporated

Typical Characteristics (continued)

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

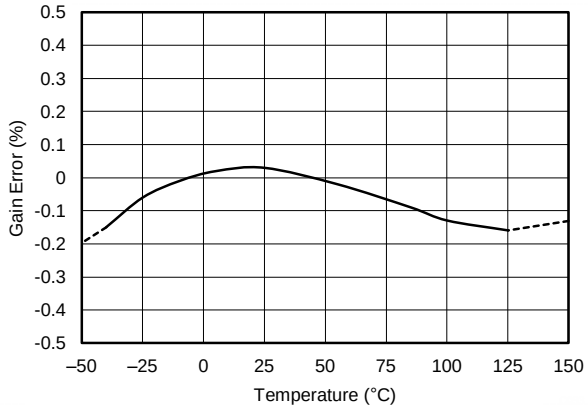
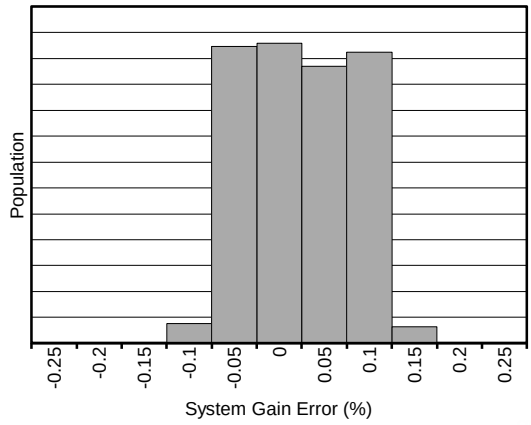


Figure 13. System Gain Error vs Temperature



System gain error = R_{SHUNT} error + amplifier gain error, load current = 10 A

Figure 14. System Gain Error Distribution

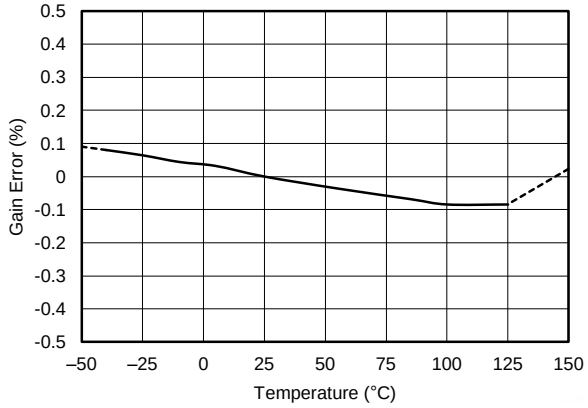
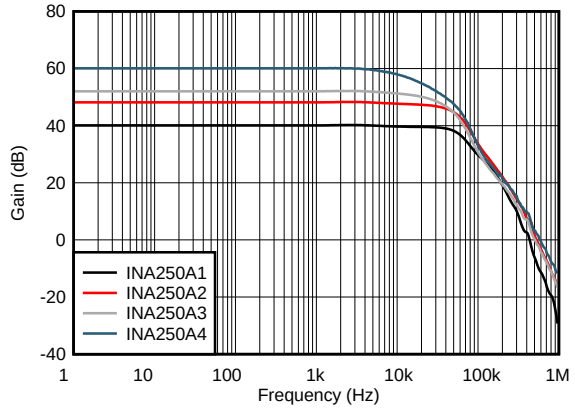
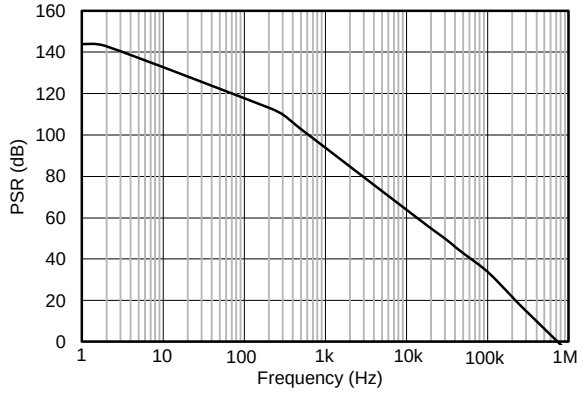


Figure 15. Amplifier Gain Error vs Temperature



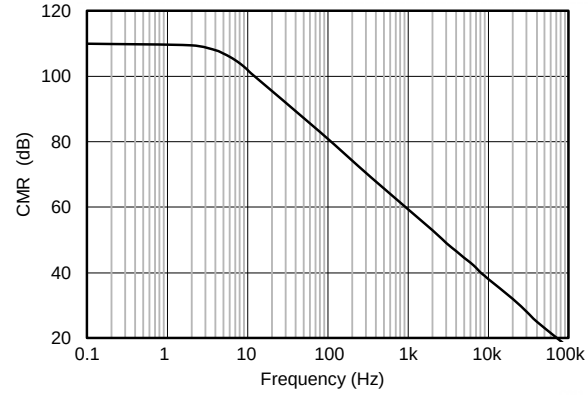
V_{CM} = 12 V, I_{SENSE} = 500 mA_{PP}

Figure 16. Amplifier Gain vs Frequency



V_{CM} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = 0 A,
VS = 5 V + 250-mV sine disturbance

Figure 17. Power-Supply Rejection vs Frequency



VS = 5 V, V_{REF} = 2.5 V, I_{SENSE} = 0 A, V_{CM} = 1-V sine wave

Figure 18. Common-Mode Rejection vs Frequency

Copyright © 2015, Texas Instruments Incorporated

Typical Characteristics (continued)

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

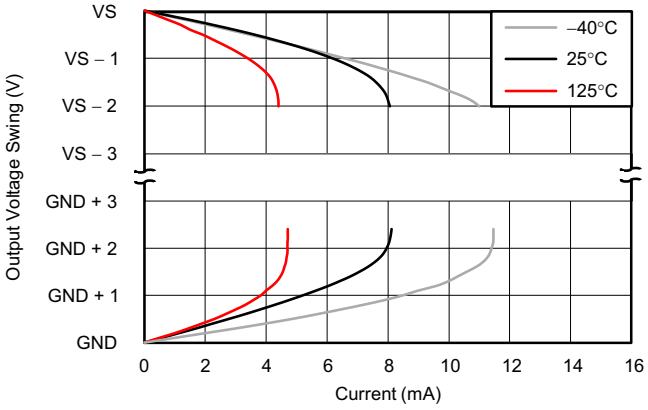
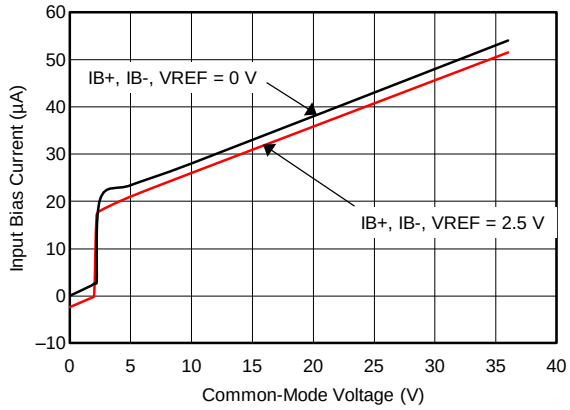
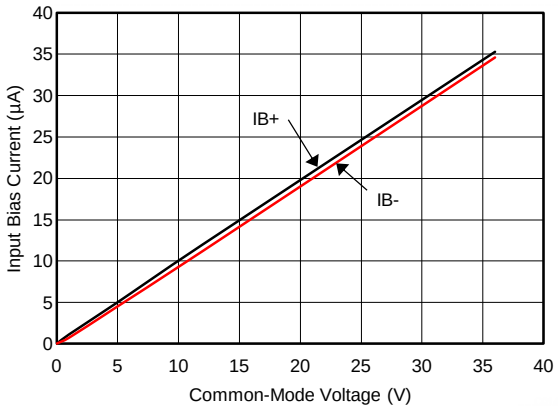


Figure 19. Output Voltage Swing vs Output Current



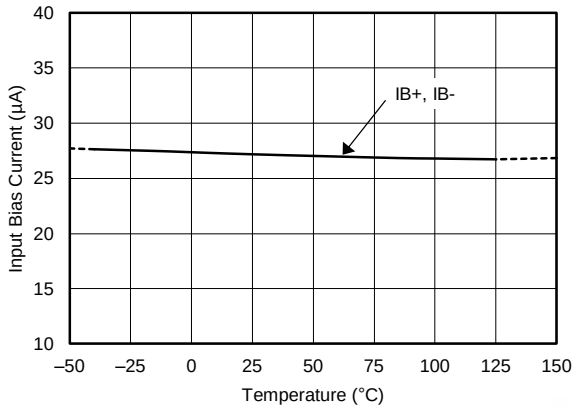
I_{SENSE} = 0 A, VS = 5 V

Figure 20. Input Bias Current vs Common-Mode Voltage (VS = 5 V)



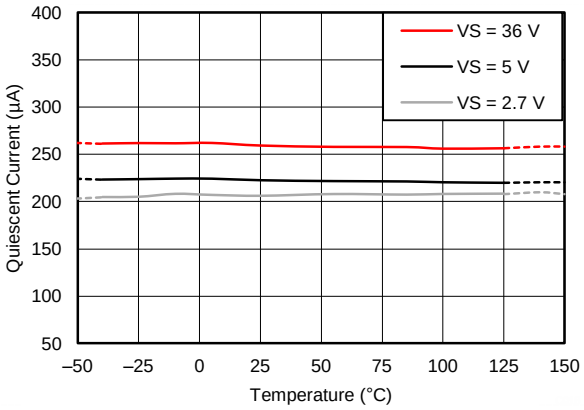
I_{SENSE} = 0 A, VS = 0 V, VREF = 0 V

Figure 21. Input Bias Current vs Common-Mode Voltage (VS = 0 V)



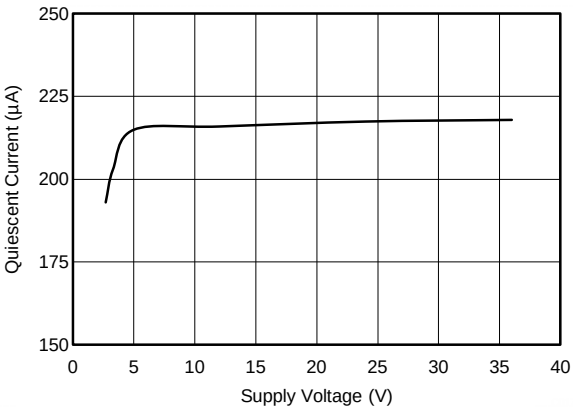
I_{SENSE} = 0 A, VS = 5 V

Figure 22. Input Bias Current vs Temperature



VREF = VS / 2

Figure 23. Quiescent Current vs Temperature



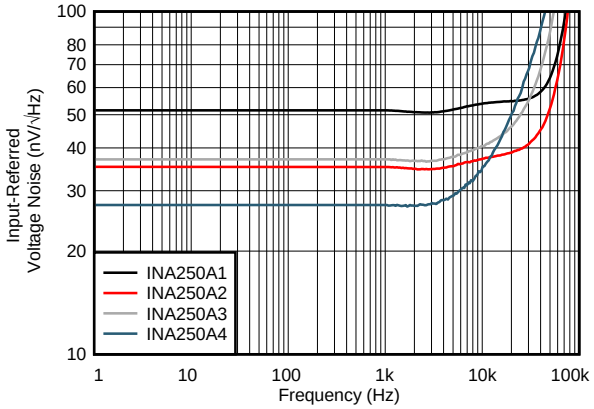
VREF = 2.5 V

Figure 24. Quiescent Current vs Supply Voltage

Copyright © 2015, Texas Instruments Incorporated

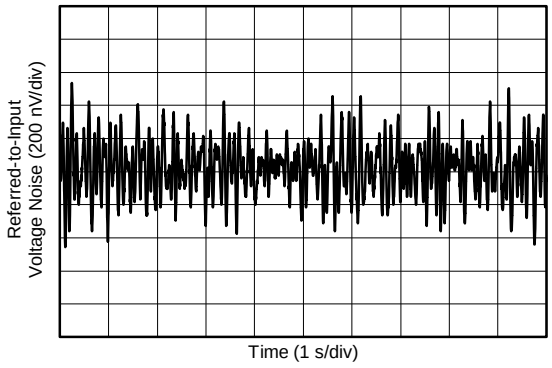
Typical Characteristics (continued)

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.



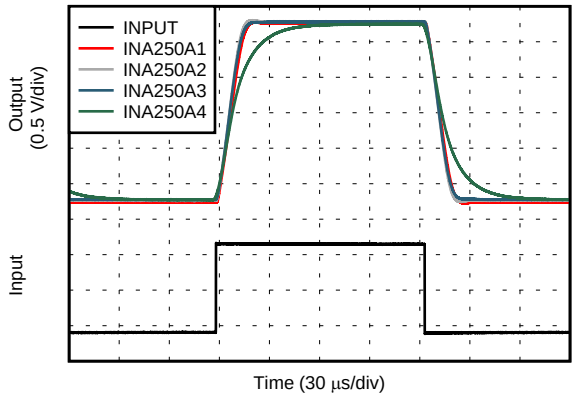
VS = 5 V, V_{REF} = 2.5 V, I_{SENSE} = 0 A

Figure 25. Input-Referred Voltage Noise vs Frequency



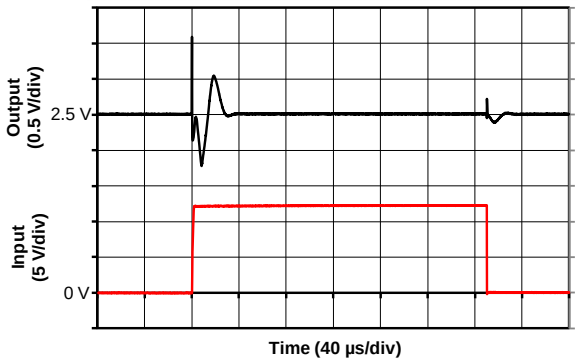
VS = 5 V, V_{CM} = 0 V, I_{SENSE} = 0 A

Figure 26. 0.1-Hz to 10-Hz Voltage Noise (Referred-to-Input)



Input = (VIN+) - (VIN-)

Figure 27. Step Response



Input = VIN+, V_{REF} = 2.5 V

Figure 28. Common-Mode Transient Response

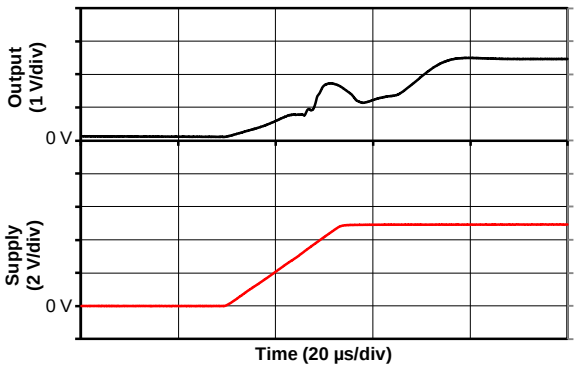


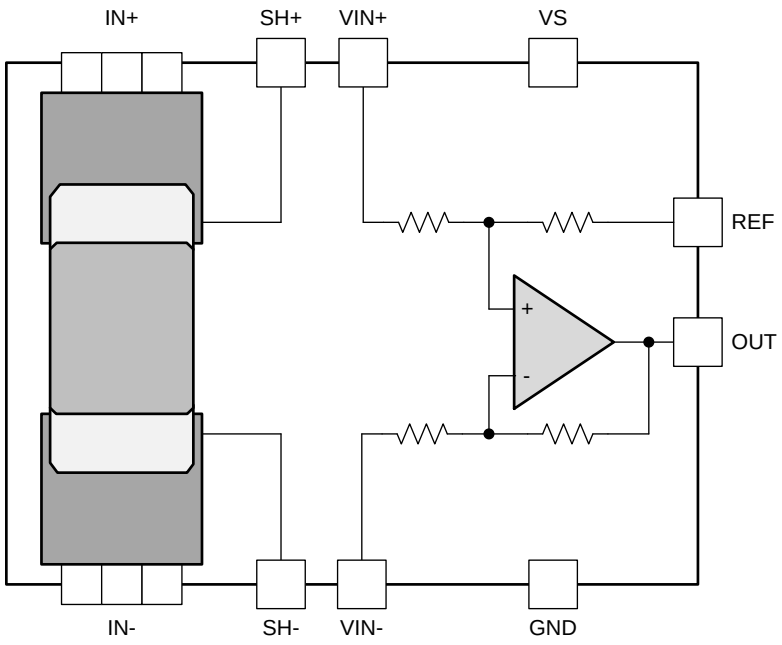
Figure 29. Start-Up Response

7 Detailed Description

7.1 Overview

The INA250 features a 2-mΩ, precision, current-sensing resistor and a 36-V common-mode, zero-drift topology, precision, current-sensing amplifier integrated into a single package. High precision measurements are enabled through the matching of the shunt resistor value and the current-sensing amplifier gain providing a highly-accurate, system-calibrated solution. Multiple gain versions are available to allow for the optimization of the desired full-scale output voltage based on the target current range expected in the application.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Integrated Shunt Resistor

The INA250 features a precise, low-drift, current-sensing resistor to allow for precision measurements over the entire specified temperature range of –40°C to 125°C. The integrated current-sensing resistor ensures measurement stability over temperature as well as improving layout and board constraint difficulties common in high precision measurements.

The onboard current-sensing resistor is designed as a 4-wire (or Kelvin) connected resistor that enables accurate measurements through a force-sense connection. Connecting the amplifier inputs pins (VIN– and VIN+) to the sense pins of the shunt resistor (SH– and SH+) eliminates many of the parasitic impedances commonly found in typical very-low sensing-resistor level measurements. Although the sense connection of the current-sensing resistor can be accessed via the SH+ and SH– pins, this resistor is not intended to be used as a stand-alone component. The INA250 is system-calibrated to ensure that the current-sensing resistor and current-sensing amplifier are both precisely matched to one another. Use of the shunt resistor without the onboard amplifier results in a current-sensing resistor tolerance of approximately 5%. To achieve the optimized system gain specification, the onboard sensing resistor must be used with the internal current-sensing amplifier.

Copyright © 2015, Texas Instruments Incorporated

Feature Description (continued)

The INA250 has approximately 4.5 mΩ of package resistance. 2 mΩ of this total package resistance is a precisely-controlled resistance from the Kelvin-connected current-sensing resistor used by the amplifier. The power dissipation requirements of the system and package are based on the total 4.5-mΩ package resistance between the IN+ and IN– pins. The heat dissipated across the package when current flows through the device ultimately determines the maximum current that can be safely handled by the package. The current consumption of the silicon is relatively low, leaving the total package resistance carrying the high load current as the primary contributor to the total power dissipation of the package. The maximum safe-operating current level is set to ensure that the heat dissipated across the package is limited so that no damage to the resistor or the package itself occurs or that the internal junction temperature of the silicon does not exceed a 150°C limit.

External factors (such as ambient temperature, external air flow, and PCB layout) can contribute to how effectively the heat developed as a result of the current flowing through the total package resistance can be removed from within the device. Under the conditions of no air flow, a maximum ambient temperature of 85°C, and 1-oz. copper input power planes, the INA250 can accommodate continuous current levels up to 15 A. As shown in Figure 30, the current handling capability is derated at temperatures above the 85°C level with safe operation up to 10 A at a 125°C ambient temperature. With air flow and larger 2-oz. copper input power planes, the INA250 can safely accommodate continuous current levels up to 15 A over the entire –40°C to 125°C temperature range.

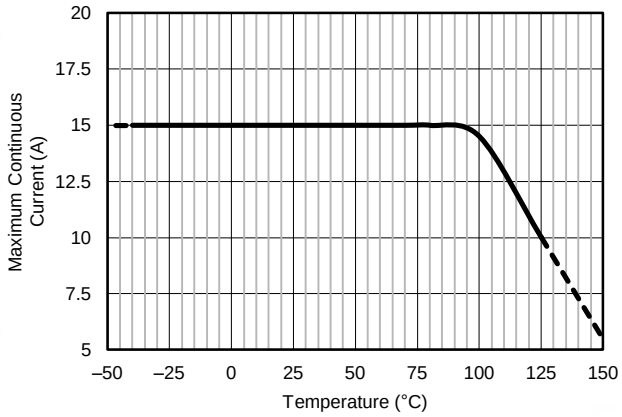


Figure 30. Maximum Current vs Temperature

7.3.2 Short-Circuit Duration

The INA250 features a physical shunt resistance that is able to withstand current levels higher than the continuous handling limit of 15 A without sustaining damage to the current-sensing resistor or the current-sensing amplifier if the excursions are very brief. Figure 31 shows the short-circuit duration curve for the INA250.

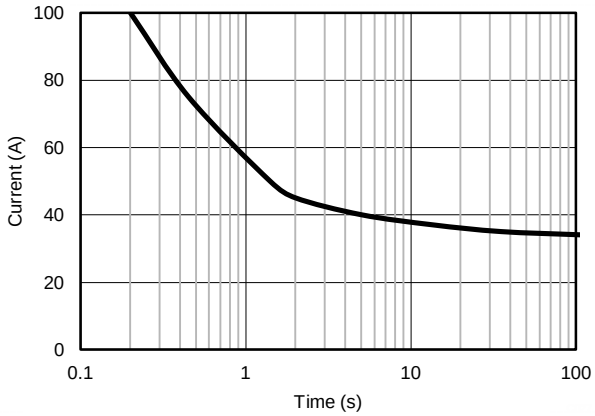


Figure 31. Short-Circuit Duration

Feature Description (continued)

7.3.3 Temperature Stability

System calibration is common for many industrial applications to eliminate initial component and system-level errors that can be present. A system-level calibration can reduce the initial accuracy requirement for many of the individual components because the errors associated with these components are effectively eliminated through the calibration procedure. Performing this calibration can enable precision measurements at the temperature in which the system is calibrated, but as the system temperature changes as a result of external ambient changes or due to self heating, measurement errors are reintroduced. Without accurate temperature compensation used in addition to the initial adjustment, the calibration procedure is not effective in accounting for these temperature-induced changes. One of the primary benefits of the very low temperature coefficient of the INA250 (including both the integrated current-sensing resistor and current-sensing amplifier) is ensuring that the device measurement remains highly accurate, even when the temperature changes throughout the specified temperature range of the device.

For the integrated current-sensing resistor, the drift performance is shown in Figure 32. Although several temperature ranges are specified in the *Electrical Characteristics* table, applications operating in ranges other than those described can use Figure 32 to determine how much variance in the shunt resistor value can be expected. As with any resistive element, the tolerance of the component varies when exposed to different temperature conditions. For the current-sensing resistor integrated in the INA250, the resistor does vary slightly more when operated in temperatures ranging from –40°C to 0°C than when operated from 0°C to 125°C. However, even in the –40°C to 0°C temperature range, the drift is still quite low at 25 ppm/°C.

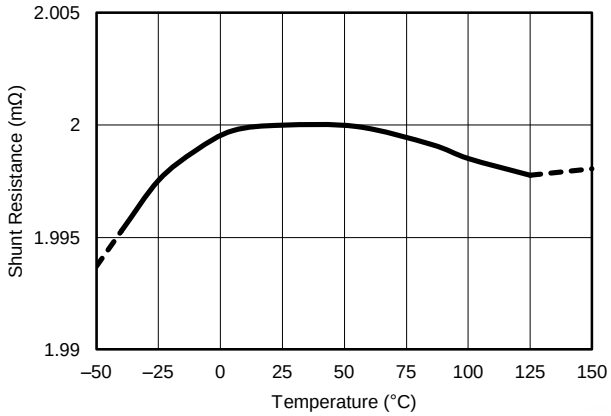


Figure 32. Sensing Resistor vs Temperature

An additional aspect to consider is that when current flows through the current-sensing resistor, power is dissipated across this component. This dissipated power results in an increase in the internal temperature of the package, including the integrated sensing resistor. This resistor self-heating effect results in an increase of the resistor temperature helping to move the component out of the colder, wider drift temperature region.

Copyright © 2015, Texas Instruments Incorporated

7.4 Device Functional Modes

7.4.1 Amplifier Operation

The INA250 current-sense amplifier can be configured to measure both unidirectional and bidirectional currents through the reference voltage level applied to the reference pin, REF. The reference voltage connected to REF sets the output level that corresponds with a zero input current condition. For unidirectional operation, tie the REF pin to ground so that when the current increases, the output signal also increases upwards from this reference voltage (or ground in this case). For bidirectional currents, an external voltage source can be used as the reference voltage connected to the REF pin to bias up the output. Set the reference voltage to enable sufficient range above and below this level based on the expected current range to be measured. Positive currents result in an output signal that increases from the zero-current output level set by the reference voltage whereas negative currents result in an output signal that decreases.

For both unidirectional and bidirectional applications, the amplifier transfer function is shown in Equation 1:

$$V_{OUT} = (I_{LOAD} \times GAIN) + V_{REF} \quad (1)$$

where:

- I_{LOAD} is the current being measured passing through the internal shunt resistor,
- GAIN is the corresponding gain (mA/V) of the selected device, and
- V_{REF} is the voltage applied to the REF pin

As with any difference amplifier, the INA250 common-mode rejection ratio is affected by any impedance present at the REF input. This concern is not a problem when the REF pin is connected directly to a reference or power supply. When using resistive dividers from a power supply or a reference voltage, buffer the REF pin with an op amp.

7.4.2 Input Filtering

An obvious and straightforward location for filtering is at the device output; however, this location negates the advantage of the low output impedance of the output stage buffer. The input then represents the best location for implementing external filtering. Figure 33 shows the typical implementation of the input filter for the device.

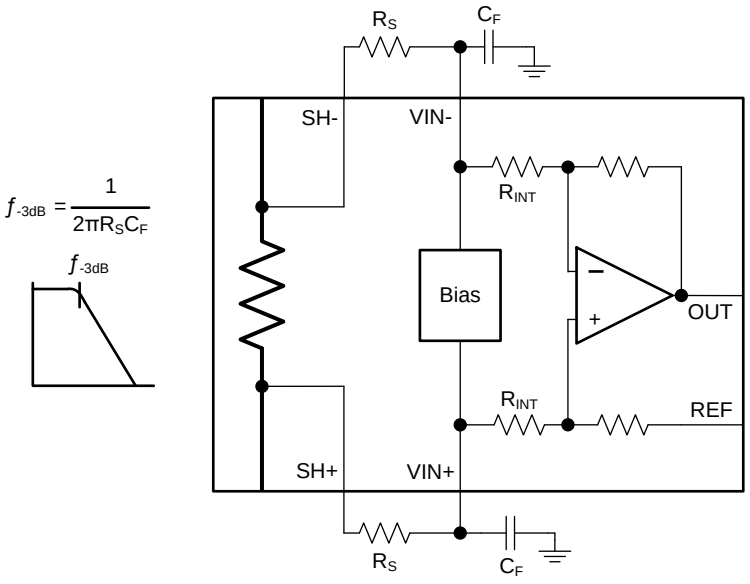


Figure 33. Input Filter

Device Functional Modes (continued)

The addition of external series resistance at the input pins to the amplifier, however, creates an additional error in the measurement. Keep the value of these series resistors to 10 Ω or less, if possible, to reduce the affect to accuracy. The internal bias network illustrated in Figure 33 present at the input pins creates a mismatch in input bias currents when a differential voltage is applied between the input pins, as shown in Figure 34.

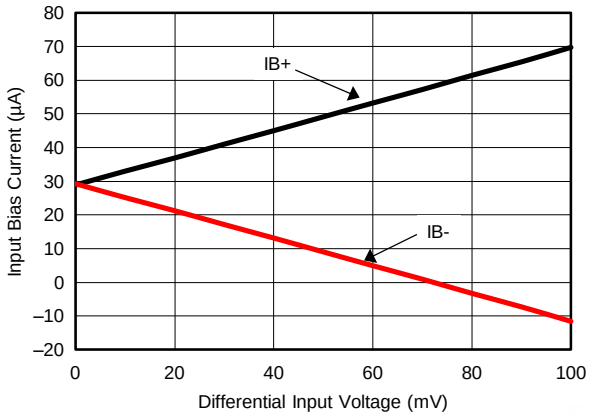


Figure 34. Input Bias Current vs Differential Input Voltage

7.4.2.1 Calculating Gain Error Resulting from External Filter Resistance

If additional external series filter resistors are added to the circuit, the mismatch in bias currents results in a mismatch of voltage drops across the filter resistors. This mismatch creates a differential error voltage that subtracts from the voltage developed across the Kelvin connection of the shunt resistor, thus reducing the voltage that reaches the amplifier input terminals. Without the additional series resistance, the mismatch in input bias currents has little effect on device operation as a result of the low input bias current of the amplifier and the typically low impedance of the traces between the shunt and amplifier input pins. The amount of error these external filter resistors add to the measurement can be calculated using Equation 3, where the gain error factor is calculated using Equation 2.

The amount of variance between the differential voltage present at the device input relative to the voltage developed at the shunt resistor is based both on the external series resistance value as well as the internal input resistors, R_{INT}; see Figure 33. The reduction of the shunt voltage reaching the device input pins appears as a gain error when comparing the output voltage relative to the voltage across the shunt resistor. A factor can be calculated to determine the amount of gain error that is introduced by the addition of external series resistance. Equation 2 calculates the expected deviation from the shunt voltage compared to the expected voltage at the device input pins.

$$\text{Gain Error Factor} = \frac{(1250 \times R_{INT})}{(1250 \times R_S) + (1250 \times R_{INT}) + (R_S \times R_{INT})} \quad (2)$$

where:

- R_{INT} is the internal input resistor and
- R_S is the external series resistance

$$\text{Gain Error (\%)} = 100 - (100 \times \text{Gain Error Factor}) \quad (3)$$

With the adjustment factor equation including the device internal input resistance, this factor varies with each gain version; see Table 1. Each individual device gain error factor is listed in Table 2.

The gain error that can be expected from the addition of the external series resistors can then be calculated based on Equation 3.

Copyright © 2015, Texas Instruments Incorporated

Device Functional Modes (continued)

Table 1. Input Resistance

DEVICE	GAIN	R_{INT}
INA250A1	200 mV/A	50 kΩ
INA250A2	500 mV/A	20 kΩ
INA250A3	800 mV/A	12.5 kΩ
INA250A4	2 V/A	5 kΩ

Table 2. Device Gain Error Factor

DEVICE	SIMPLIFIED GAIN ERROR FACTOR
INA250A1	$\frac{50{,}000}{(41 \bullet R_S) + 50{,}000}$
INA250A2	$\frac{20{,}000}{(17 \bullet R_S) + 20{,}000}$
INA250A3	$\frac{12{,}500}{(11 \bullet R_S) + 12{,}500}$
INA250A4	$\frac{1{,}000}{R_S + 1{,}000}$

For example, using an INA250A2 and the corresponding gain error equation from Table 2, a series resistance of 10 Ω results in a gain error factor of 0.991. The corresponding gain error is then calculated using Equation 3, resulting in a gain error of approximately 0.84% because of the external 10-Ω series resistors.

7.4.3 Shutting Down the Device

Although the device does not have a shutdown pin, the low power consumption allows for the device to be powered from the output of a logic gate or transistor switch that can turn on and turn off the voltage connected to the device power-supply pin. However, in current-shunt monitoring applications, there is also a concern for how much current is drained from the shunt circuit in shutdown conditions. Evaluating this current drain involves considering the device simplified schematic in shutdown mode, as shown in Figure 35.

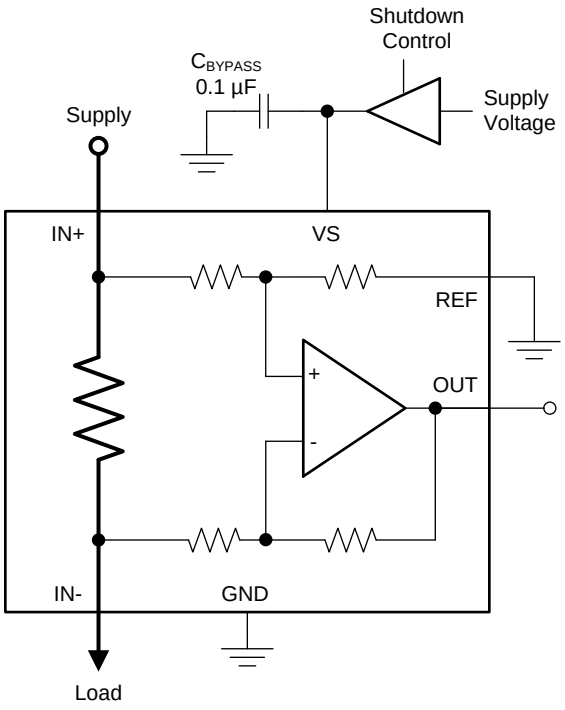


Figure 35. Shutting Down the Device

Note that there is typically an approximate 1-MΩ impedance (from the combination of the feedback and input resistors) from each device input to the REF pin. The amount of current flowing through these pins depends on the respective configuration. For example, if the REF pin is grounded, calculating the effect of the 1-MΩ impedance from the shunt to ground is straightforward. However, if the reference or op amp is powered when the device is shut down, the calculation is direct. Instead of assuming 1 MΩ to ground, assume 1 MΩ to the reference voltage. If the reference or op amp is also shut down, some knowledge of the reference or op amp output impedance under shutdown conditions is required. For instance, if the reference source functions similar to an open circuit when un-powered, little or no current flows through the 1-MΩ path.

7.4.4 Using the Device with Common-Mode Transients Above 36 V

With a small amount of additional circuitry, the device can be used in circuits subject to transients higher than 36 V (such as in automotive applications). Use only zener diodes or zener-type transient absorbers (sometimes referred to as *transzorbs*); any other type of transient absorber has an unacceptable time delay. Start by adding a pair of resistors, as shown in Figure 36, as a working impedance for the zener. Keeping these resistors as small as possible is preferable, most often approximately 10 Ω. This value limits the affect on accuracy with the addition of these external components, as described in the *Input Filtering* section. Device interconnections between the shunt resistor and amplifier have a current handling limit of 1 A. Using a 10-Ω resistor limits the allowable transient range to 10 V above the zener clamp in order to not damage the device. Larger resistor values can be used in this protection circuit to accommodate a larger transient voltage range, resulting in a larger affect on gain error. Because this circuit limits only short-term transients, many applications are satisfied with a 10-Ω resistor along with conventional zener diodes of the lowest power rating available.

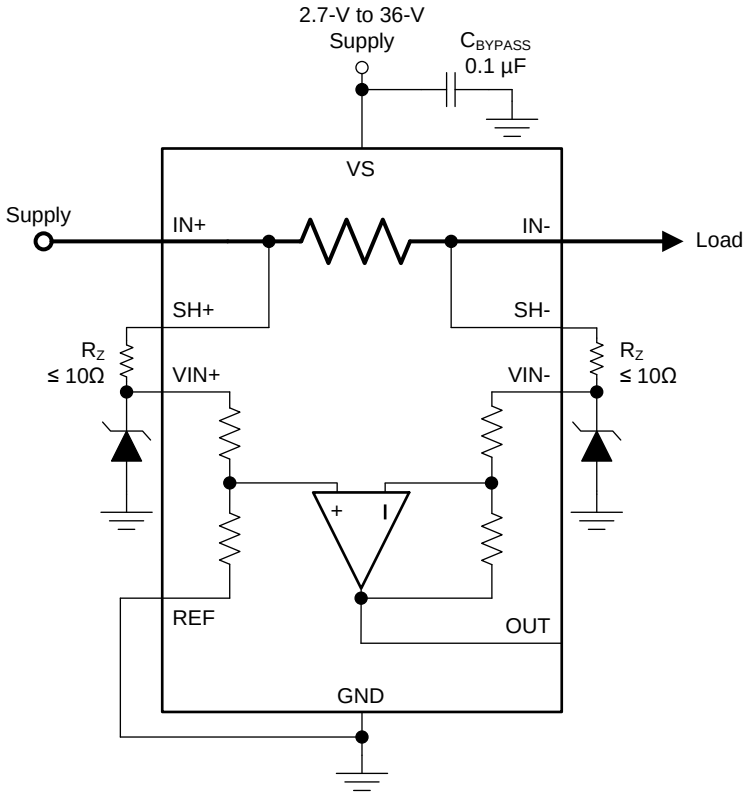


Figure 36. Device Transient Protection

Copyright © 2015, Texas Instruments Incorporated

8 Applications and Implementation

NOTE

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

8.1 Application Information

The INA250 measures the voltage developed across the internal current-sensing resistor when current passes through it. The ability to drive the reference pin to adjust the functionality of the output signal offers multiple configurations, as discussed in this section.

8.2 Typical Applications

8.2.1 Current Summing

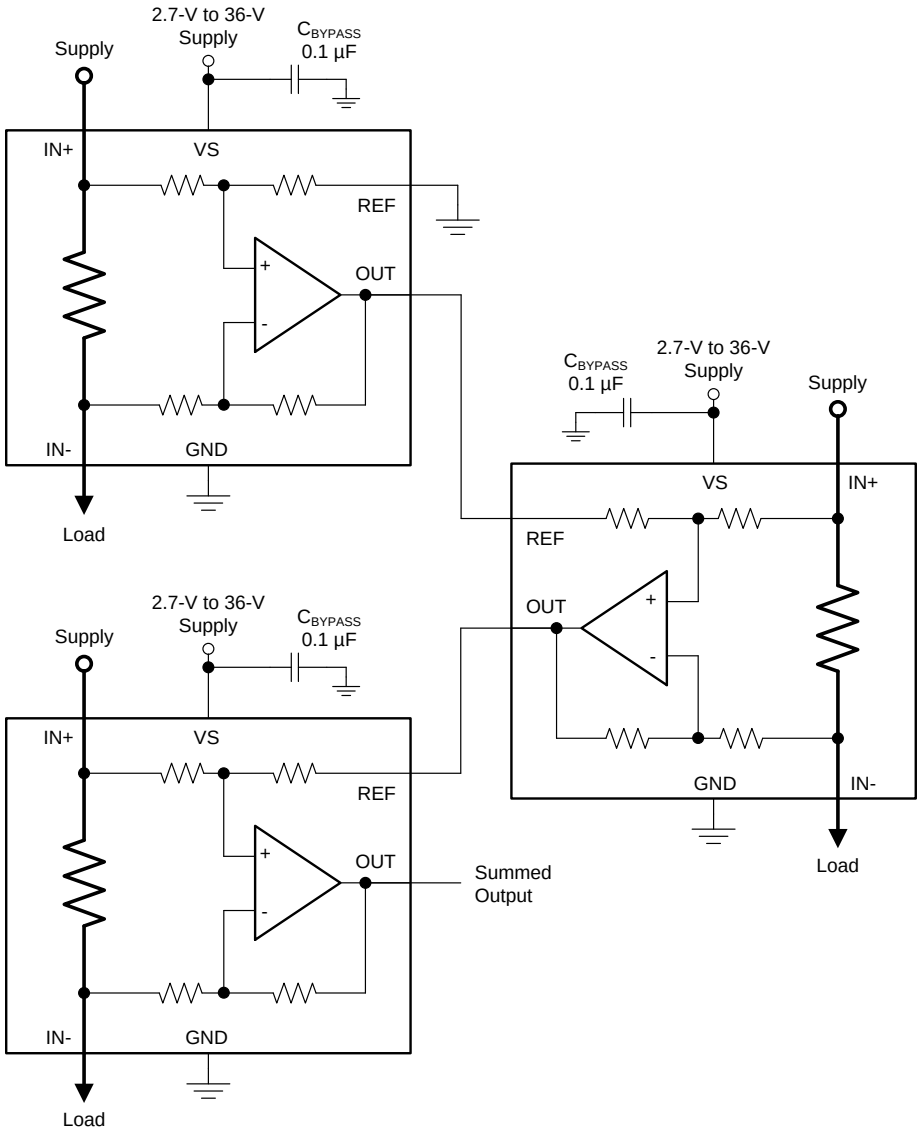


Figure 37. Daisy-Chain Configuration

Typical Applications (continued)

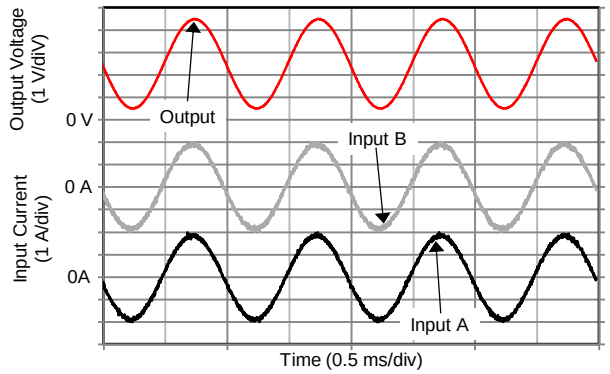
8.2.1.1 Design Requirements

Three daisy-chained devices are illustrated in Figure 37. The reference input of the first INA250 sets the quiescent level on the output of all the INA250 devices in the string.

8.2.1.2 Detailed Design Procedure

The outputs of multiple INA250 devices are easily summed by connecting the output signal of one INA250 to the reference input of a second INA250. Summing beyond two devices is possible by repeating this configuration, connecting the output signal of the next INA250 to the reference pin of a subsequent INA250 in the chain. The output signal of the final INA250 in this chain includes the current level information for all channels in the chain.

8.2.1.3 Application Curve



VS = 5 V, V_{REF} = 2.5 V

Figure 38. Daisy-Chain Configuration Output Response

Copyright © 2015, Texas Instruments Incorporated

Typical Applications (continued)

8.2.2 Parallel Multiple INA250 Devices for Higher Current

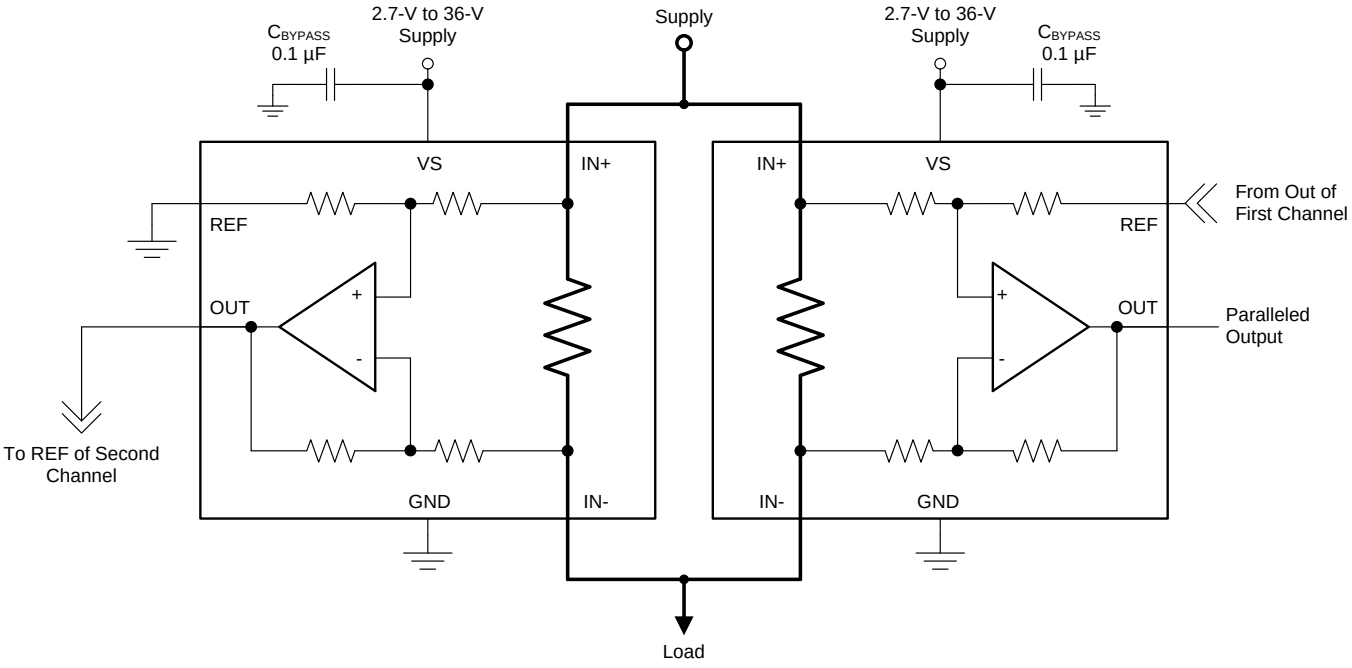


Figure 39. Parallel Summing Configuration

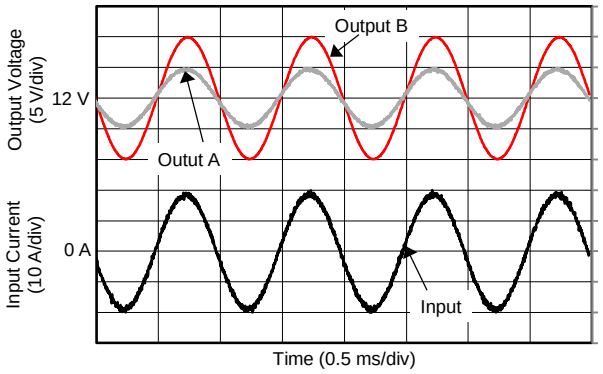
8.2.2.1 Design Requirements

The parallel connection for multiple INA250 devices can be used to reduce the equivalent overall sense resistance, enabling monitoring of higher current levels than a single device is able to accommodate alone. This configuration also uses a summing arrangement, as described in the *Current Summing* section. A parallel summing configuration is shown in Figure 39.

8.2.2.2 Detailed Design Procedure

With a summing configuration the output of the first channel is fed into the reference input of the second, adding the distributed measurements back together into a single measured value.

8.2.2.3 Application Curve



VS = 24 V, V_{REF} = 12 V

Figure 40. Parallel Configuration Output Response

Copyright © 2015, Texas Instruments Incorporated

Typical Applications (continued)

8.2.3 Current Differencing

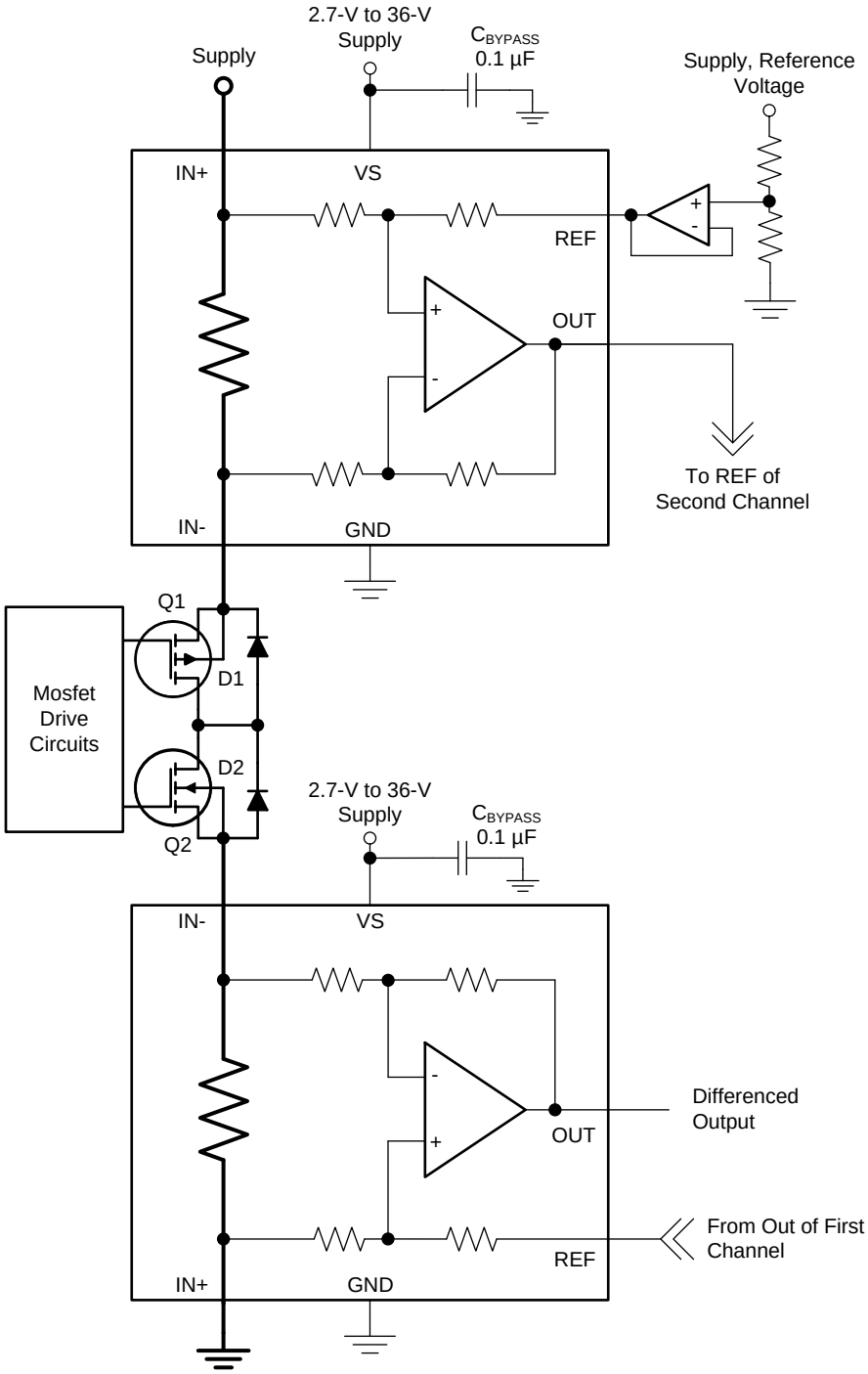


Figure 41. Current Differencing Configuration

Copyright © 2015, Texas Instruments Incorporated

Typical Applications (continued)

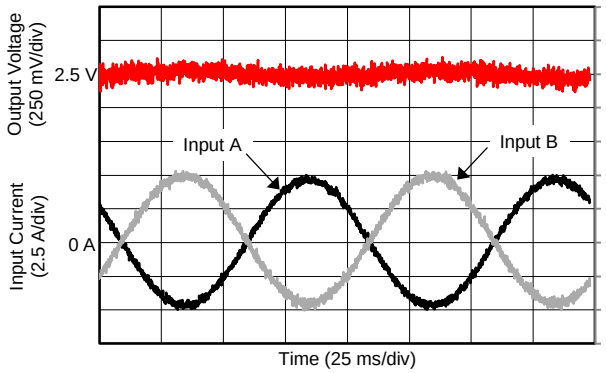
8.2.3.1 Design Requirements

Occasionally, the need may arise to confirm that the current into a load is identical to the current coming out of a load, such as when performing diagnostic testing or fault detection. This procedure requires precision current differencing. This method is the same as current summing, except that the two amplifiers have the respective inputs connected opposite of each other. Under normal operating conditions, the final output is very close to the reference value and proportional to any current difference. Figure 41 is an example of two INA250 devices connected for current differencing.

8.2.3.2 Detailed Design Procedure

The load current can also be measured directly at the output of the first channel. Although technically this configuration is current differencing, this connection (see Figure 41) is really intended to allow the upper (positive) sense channel to report any positive-going excursions in the overall output and the lower (negative) sense channel to report any negative-going excursions.

8.2.3.3 Application Curve



VS = 5 V, V_{REF} = 2.5 V

Figure 42. Current Differencing Configuration Output Response

9 Power Supply Recommendations

The input circuitry of the device can accurately measure signals on common-mode voltages beyond the power-supply voltage, VS. For example, the voltage applied to the VS power-supply pin can be 5 V, whereas the load power-supply voltage being monitored (the common-mode voltage) can be as high as 36 V. Note also that the device can withstand the full 0-V to 36-V range at the input pins, regardless of whether the device has power applied or not. Power-supply bypass capacitors are required for stability and must be placed as closely as possible to the supply and ground pins of the device. A typical value for this supply bypass capacitor is 0.1 µF. Applications with noisy or high-impedance power supplies can require additional decoupling capacitors to reject power-supply noise.

Copyright © 2015, Texas Instruments Incorporated

10 Layout

10.1 Layout Guidelines

- The INA250 is specified for current handling of up to 10 A over the entire –40°C to 125°C temperature range using a 1-oz. copper pour for the input power plane as well as no external airflow passing over the device.
- The primary current-handling limitation for the INA250 is how much heat is dissipated inside the package. Efforts to improve heat transfer out of the package and into the surrounding environment improve the ability of the device to handle currents of up to 15 A over the entire –40°C to 125°C temperature range.
- Heat transfer improvements primarily involve larger copper power traces and planes with increased copper thickness (2 oz.) as well as providing airflow to pass over the device. The INA250EVM features a 2-oz. copper pour for the planes and is capable of supporting 15 A at temperatures up to 125°C.
- Place the power-supply bypass capacitor as close as possible to the supply and ground pins. The recommended value of this bypass capacitor is 0.1 µF. Additional decoupling capacitance can be added to compensate for noisy or high-impedance power supplies.

10.2 Layout Examples

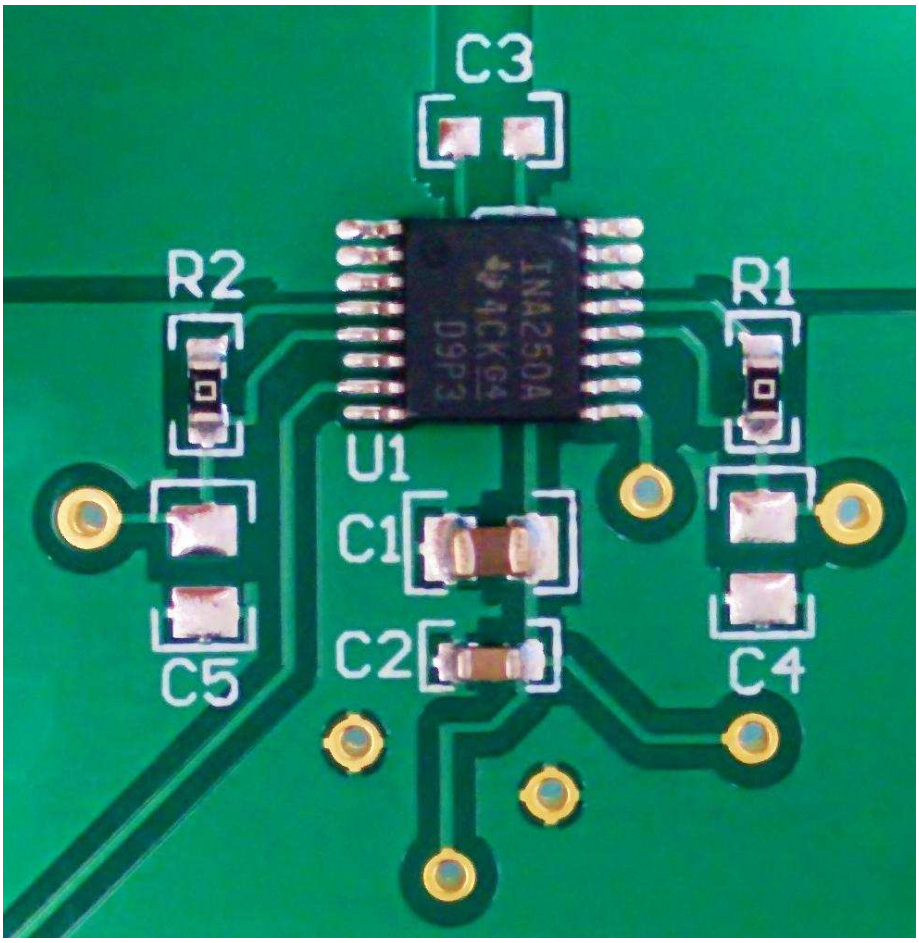


Figure 43. Recommended Layout

Copyright © 2015, Texas Instruments Incorporated

Layout Examples (continued)

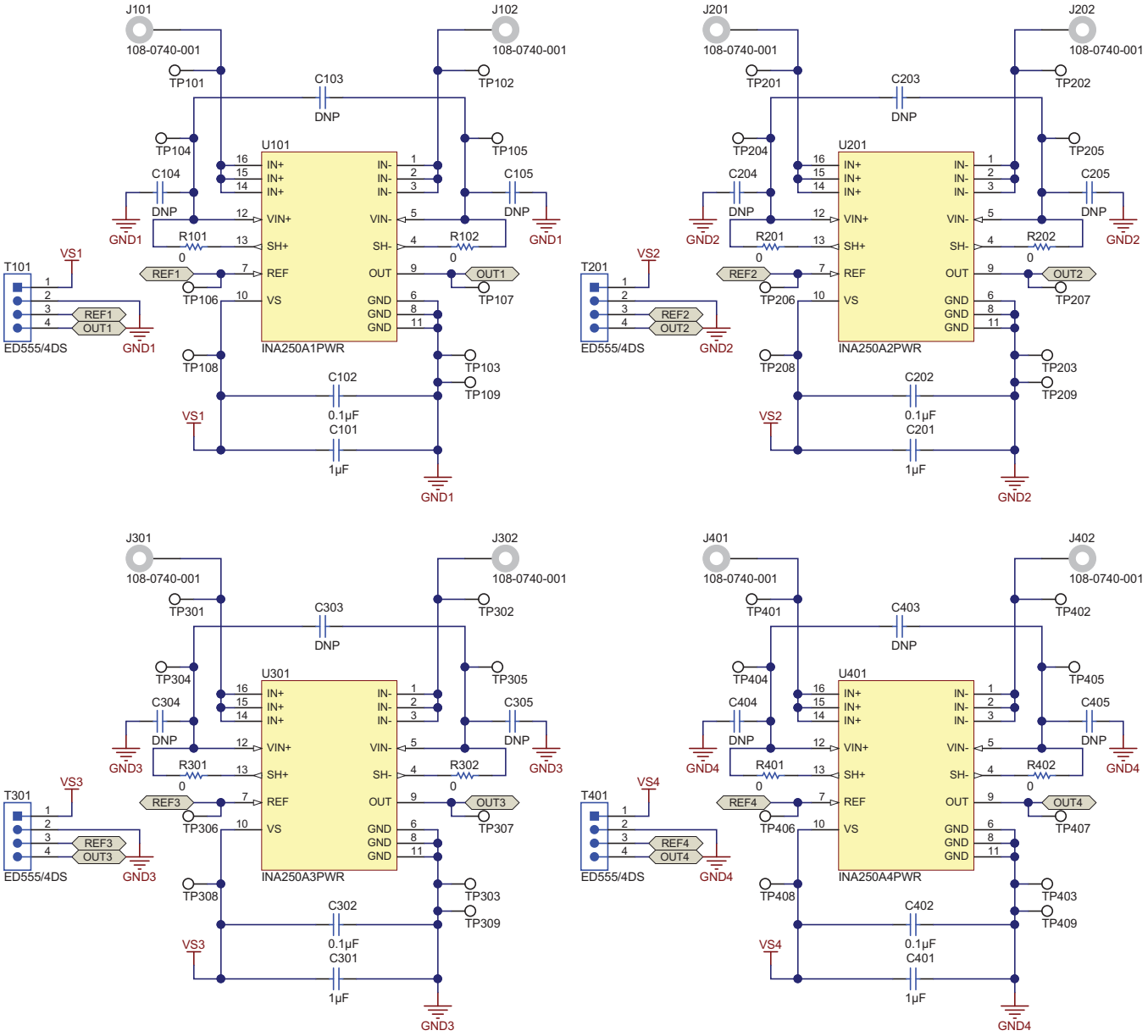


Figure 44. Recommended Layout Schematic

11 Device and Documentation Support

11.1 Documentation Support

11.1.1 Related Documentation

- INA250EVM User Guide, SBOU153

11.2 Related Links

The table below lists quick access links. Categories include technical documents, support and community resources, tools and software, and quick access to sample or buy.

Table 3. Related Links

PARTS	PRODUCT FOLDER	SAMPLE & BUY	TECHNICAL DOCUMENTS	TOOLS & SOFTWARE	SUPPORT & COMMUNITY
INA250A1	Click here	Click here	Click here	Click here	Click here
INA250A2	Click here	Click here	Click here	Click here	Click here
INA250A3	Click here	Click here	Click here	Click here	Click here
INA250A4	Click here	Click here	Click here	Click here	Click here

11.3 Community Resources

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's Terms of Use.

TI E2E™ Online Community ***TI's Engineer-to-Engineer (E2E) Community.*** Created to foster collaboration among engineers. At e2e.ti.com, you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

Design Support ***TI's Design Support*** Quickly find helpful E2E forums along with design support tools and contact information for technical support.

11.4 Trademarks

E2E is a trademark of Texas Instruments.
All other trademarks are the property of their respective owners.

11.5 Electrostatic Discharge Caution



This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

11.6 Glossary

SLYZ022 — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

Copyright © 2015, Texas Instruments Incorporated

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
INA250A1PW	PREVIEW	TSSOP	PW	16		Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A1	
INA250A1PWR	PREVIEW	TSSOP	PW	16		Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A1	
INA250A2PW	ACTIVE	TSSOP	PW	16	90	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A2	Samples
INA250A2PWR	ACTIVE	TSSOP	PW	16	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A2	Samples
INA250A3PW	PREVIEW	TSSOP	PW	16		Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A3	
INA250A3PWR	PREVIEW	TSSOP	PW	16		Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A3	
INA250A4PW	PREVIEW	TSSOP	PW	16		Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A4	
INA250A4PWR	PREVIEW	TSSOP	PW	16		Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	I250A4	

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
TBD: The Pb-Free/Green conversion plan has not been defined.
Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.
Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

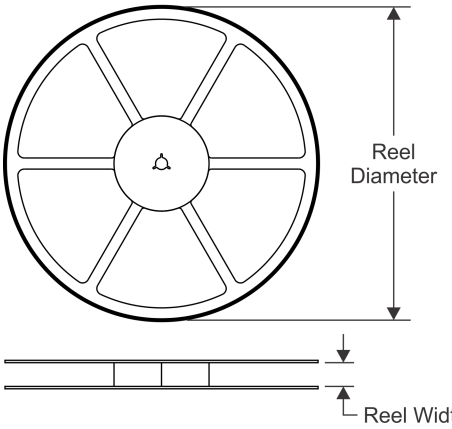
(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

Important Information and Disclaimer: The information provided on this page represents TI's knowledge and belief as of the date that it is provided. TI bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. TI has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

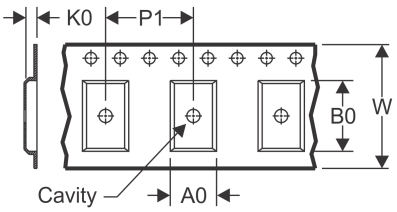
In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.

TAPE AND REEL INFORMATION

REEL DIMENSIONS

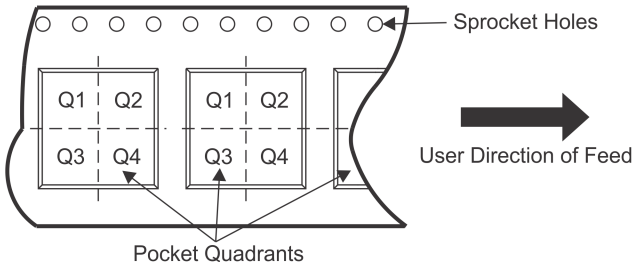


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

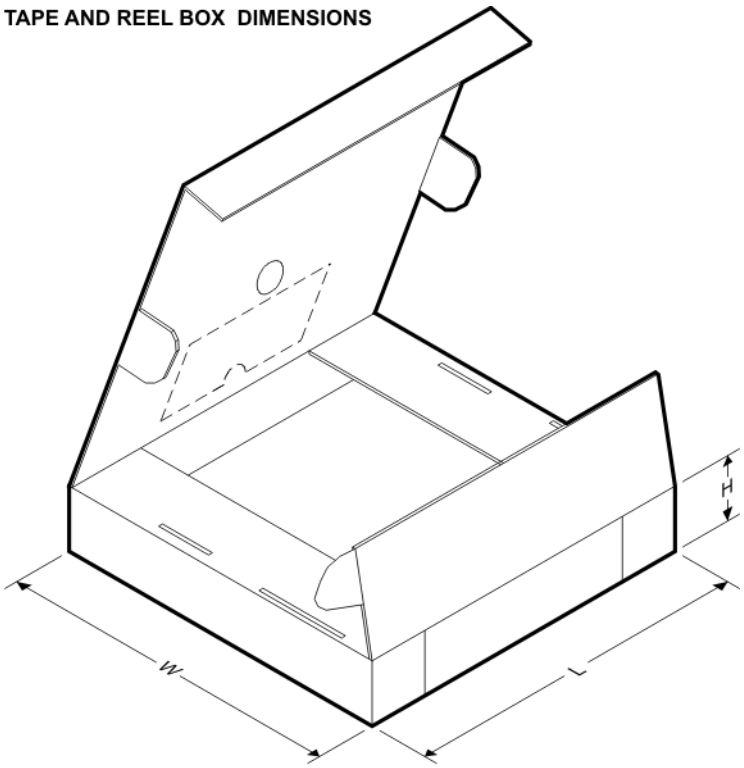
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
INA250A2PWR	TSSOP	PW	16	2000	330.0	12.4	6.9	5.6	1.6	8.0	12.0	Q1

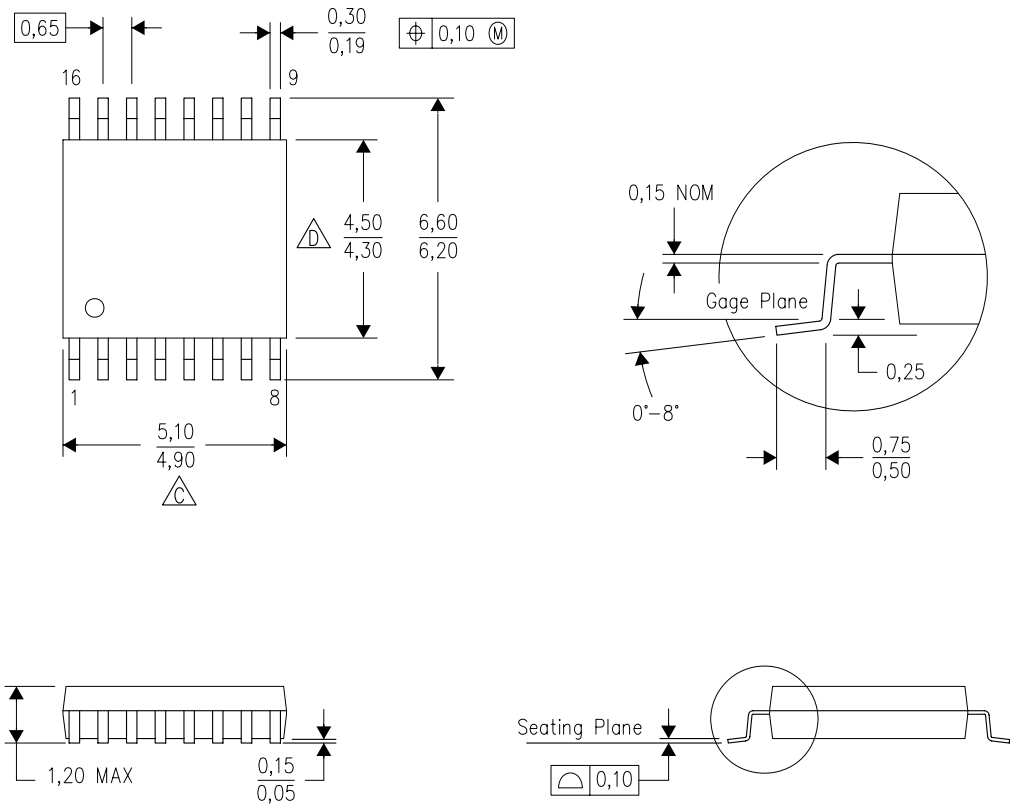
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
INA250A2PWR	TSSOP	PW	16	2000	367.0	367.0	35.0

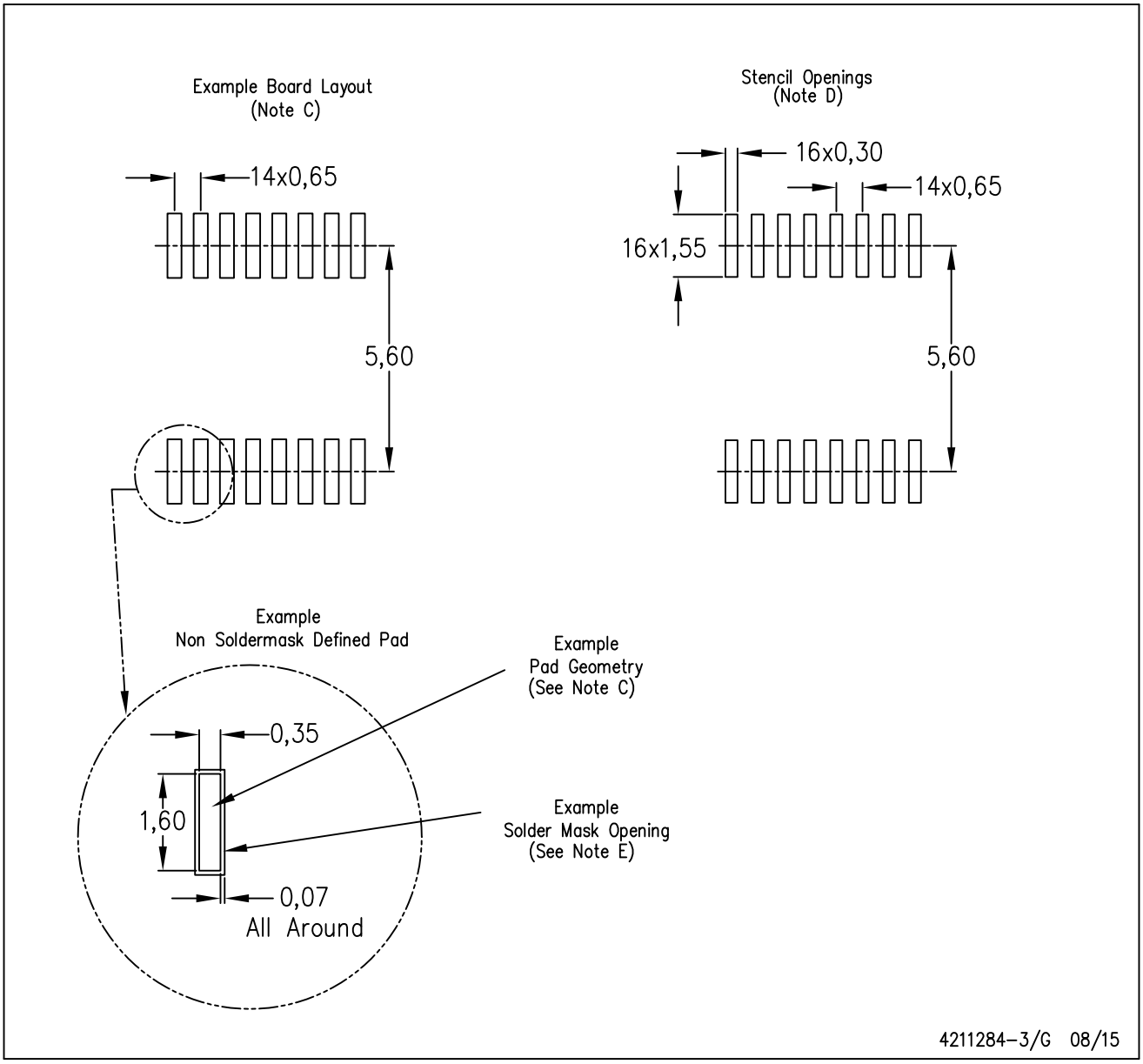
PW (R–PDSO–G16) PLASTIC SMALL OUTLINE



4040064–4/G 02/11

NOTES:
A. All linear dimensions are in millimeters. Dimensioning and tolerancing per ASME Y14.5M–1994.
B. This drawing is subject to change without notice.
C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0,15 each side.
D. Body width does not include interlead flash. Interlead flash shall not exceed 0,25 each side.
E. Falls within JEDEC MO–153

PW (R–PDSO–G16) PLASTIC SMALL OUTLINE



NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Publication IPC–7351 is recommended for alternate designs.
D. Laser cutting apertures with trapezoidal walls and also rounding corners will offer better paste release. Customers should contact their board assembly site for stencil design recommendations. Refer to IPC–7525 for other stencil recommendations.
E. Customers should contact their board fabrication site for solder mask tolerances between and around signal pads.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

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.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2015, Texas Instruments Incorporated