INA190-EP Bidirectional, Low-Power, Zero-Drift, Wide Dynamic Range, Precision Current Sense Amp With Enable

1 Features

- Supports Defense, Aerospace, and Medical Applications:
  - Temperature range: –55°C to +150°C, T_A
  - Controlled Baseline
  - One Assembly/Test Site
  - One Fabrication Site
  - Extended Product Life Cycle
  - Extended Product-Change Notification
  - Product Traceability
- Low input bias currents: 500 pA (typical) (enables microamp current measurement)
- Low power:
  - Low supply voltage, V_S: 1.7 V to 5.5 V
  - Low quiescent current: 50 µA at 25°C (typical)
- Accuracy:
  - Common-mode rejection ratio: 132 dB (minimum)
  - Gain error: ±0.2% (A1 device)
  - Gain drift: 7 ppm/°C (maximum)
  - Offset voltage, V_{OS}: ±15 µV (maximum)
  - Offset drift: 80 nV/°C (maximum)
- Wide common-mode voltage: –0.2 V to +40 V
- Bidirectional current sensing capability
- Gain options:
  - INA190A1-EP: 25 V/V
  - INA190A2-EP: 50 V/V
  - INA190A3-EP: 100 V/V
  - INA190A4-EP: 200 V/V
  - INA190A5-EP: 500 V/V

2 Applications

- Avionics
- Radar Systems
- Ruggedized Communications
- Smart Munitions
- Thermal Imaging

3 Description

The INA190-EP is a low-power, voltage-output, current-shunt monitor (also called a current-sense amplifier). This device is commonly used for overcurrent protection, precision current measurement for system optimization, or in closed-loop feedback circuits. The INA190-EP can sense drops across shunts at common-mode voltages from –0.2 V to +40 V, independent of the supply voltage.

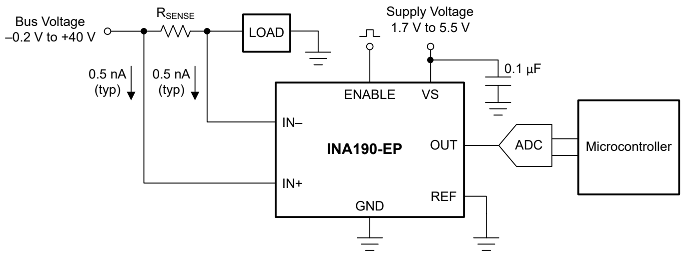
The low input bias current of the device permits the use of larger current-sense resistors, thus providing accurate current measurements in the microamp range. The low offset voltage of the zero-drift architecture extends the dynamic range of the current measurement. This feature allows for smaller sense resistors with lower power loss, while still providing accurate current measurements.

The INA190-EP operates from a single 1.7-V to 5.5-V power supply, and draws a maximum of 65 µA of supply current when enabled; only 0.1 µA when disabled. Five fixed gain options are available: 25 V/V, 50 V/V, 100 V/V, 200 V/V, or 500 V/V. The device is specified over the operating temperature range of –55°C to +150°C, and offered in the SOT-23 package.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
INA190-EP	SOT-23 (8)	1.60 mm × 2.90 mm

(1) For all available packages, see the package option addendum at the end of the data sheet.



Typical Application

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4 Revision History

DATE	REVISION	NOTES
May 2022	*	Initial release.

5 Pin Configuration and Functions

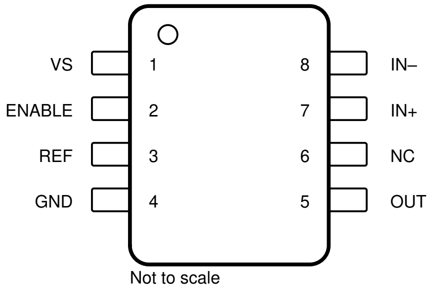


Figure 5-1. DDF Package 8-Pin Thin SOT-23 (Top View)

Table 5-1. Pin Functions

PIN		TYPE	DESCRIPTION
NAME	**NO.**		
ENABLE	2	Digital input	Enable pin. When this pin is driven to V_S, the device is on and functions as a current-sense amplifier. When this pin is driven to GND, the device is off, the supply current is reduced, and the output is placed in a high-impedance state. This pin must be driven externally, or connected to V_S if not used.
GND	4	Analog	Ground
IN–	8	Analog input	Current-sense amplifier negative input. For high-side applications, connect the to load side of the sense resistor. For low-side applications, connect to the ground side of the sense resistor.
IN+	7	Analog input	Current-sense amplifier positive input. For high-side applications, connect to the bus voltage side of the sense resistor. For low-side applications, connect to the load side of the sense resistor.
NC	6	—	Not internally connected. Either float these pins or connect to any voltage between GND and V_S.
OUT	5	Analog output	OUT pin. This pin provides an analog voltage output that is the gained-up voltage difference from the IN+ to the IN– pins, and is offset by the voltage applied to the REF pin.
REF	3	Analog input	Reference input. Enables bidirectional current sensing with an externally applied voltage.
VS	1	Analog	Power supply, 1.7 V to 5.5 V

6 Specifications

6.1 Absolute Maximum Ratings

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

			MIN	MAX	UNIT
V_S	Supply voltage			6	V
V_{IN+}, $V_{IN–}$	Analog inputs	Differential (V_{IN+}) – ($V_{IN–}$)[2]	–42	42	V
		V_{IN+}, $V_{IN–}$, with respect to GND[3]	GND – 0.3	42	
V_{ENABLE}	ENABLE		GND – 0.3	6	V
	REF, OUT[3]		GND – 0.3	(V_S) + 0.3	V
	Input current into any pin[3]			5	mA
T_A	Operating temperature		–55	150	°C
T_J	Junction temperature			150	°C
T_{stg}	Storage temperature		–65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) V_{IN+} and $V_{IN–}$ are the voltages at the IN+ and IN– pins, respectively.
(3) Input voltage at any pin may exceed the voltage shown if the current at that pin is limited to 5 mA.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001[1]	±3000	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

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

		MIN	NOM	MAX	UNIT
V_{CM}	Common-mode input range	GND – 0.2		40	V
V_{IN+}, $V_{IN–}$	Input pin voltage range	GND – 0.2		40	V
V_S	Operating supply voltage	1.7		5.5	V
V_{REF}	Reference pin voltage range	GND		V_S	V
T_A	Operating free-air temperature	–55		150	°C

6.4 Thermal Information

THERMAL METRIC[1]		INA190EP	UNIT
		DDF (SOT23)	
		8 PINS	
$R_{θJA}$	Junction-to-ambient thermal resistance	164.6	°C/W
$R_{θJC(top)}$	Junction-to-case (top) thermal resistance	86.6	°C/W
$R_{θJB}$	Junction-to-board thermal resistance	84.3	°C/W
$Ψ_{JT}$	Junction-to-top characterization parameter	7.1	°C/W
$Ψ_{JB}$	Junction-to-board characterization parameter	83.8	°C/W
$R_{θJC(bot)}$	Junction-to-case (bottom) thermal resistance	N/A	°C/W

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

6.5 Electrical Characteristics

at T_A = 25°C, V_{SENSE} = V_{IN+} – $V_{IN–}$, V_S = 1.8 V to 5.0 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, and V_{ENABLE} = V_S (unless otherwise noted)

PARAMETER		CONDITIONS		MIN	TYP	MAX	UNIT
INPUT							
CMRR	Common-mode rejection ratio	V_{SENSE} = 0 mV, V_{IN+} = –0.1 V to 40 V, T_A = –55°C to +150°C		132	150		dB
V_{OS}	Offset voltage, RTI[1]	V_S = 1.8 V, V_{SENSE} = 0 mV			–3	±15	µV
dV_{OS}/dT	Offset drift, RTI	V_{SENSE} = 0 mV, T_A = –55°C to +150°C			±10	±80	nV/°C
PSRR	Power-supply rejection ratio, RTI	V_{SENSE} = 0 mV, V_S = 1.7 V to 5.5 V, T_A = –55°C to +150°C			–1	±7	µV/V
I_{IB}	Input bias current	V_{SENSE} = 0 mV			±0.5	±3	nA
I_{IB}	Input bias current	V_{SENSE} = 0 mV, T_A = –55°C to +150°C				±20	nA
I_{IO}	Input offset current	V_{SENSE} = 0 mV			±0.07	±3	nA
I_{IO}	Input offset current	V_{SENSE} = 0 mV, T_A = –55°C to +150°C				±20	nA
OUTPUT							
G	Gain	A1 devices			25		V/V
		A2 devices			50		
		A3 devices			100		
		A4 devices			200		
		A5 devices			500		
E_G	Gain error	V_{OUT} = 0.1 V to V_S – 0.1 V	A1 devices		–0.04%	±0.2%	
			A2, A3, A4 devices		–0.06%	±0.3%	
			A5 devices		–0.08%	±0.4%	
	Gain error drift	T_A = –55°C to +150°C			2	7	ppm/°C
	Nonlinearity error[2]	V_{OUT} = 0.1 V to V_S – 0.1 V			±0.0025%	±0.025%	
RVRR	Reference voltage rejection ratio	V_{REF} = 100 mV to V_S – 100 mV, T_A = –55°C to +150°C	A1 devices		±2	±10	µV/V
			A2 devices		±1	±6	
			A3 devices		±0.5	±4	
			A4, A5 devices		±0.25	±3	
	Maximum capacitive load	No sustained oscillation			1		nF
VOLTAGE OUTPUT							
V_{SP}	Swing to V_S power-supply rail	V_S = 1.8 V, R_L = 10 kΩ to GND, T_A = –55°C to +150°C			$(V_S) – 20$	$(V_S) – 40$	mV
V_{SN}	Swing to GND	V_S = 1.8 V, R_L = 10 kΩ to GND, T_A = –55°C to +150°C, V_{SENSE} = –10 mV, V_{REF} = 0 V			$(V_{GND}) + 0.05$	$(V_{GND}) + 1$	mV
V_{ZL}	Zero current output voltage	V_S = 1.8 V, R_L = 10 kΩ to GND, T_A = –55°C to +150°C, V_{SENSE} = 0 mV, V_{REF} = 0 V	A1, A2, A3 devices		$(V_{GND}) + 1$	$(V_{GND}) + 3$	mV
			A4 devices		$(V_{GND}) + 2$	$(V_{GND}) + 4$	
			A5 devices		$(V_{GND}) + 3$	$(V_{GND}) + 9$	
FREQUENCY RESPONSE							
BW	Bandwidth[2]	A1 devices, C_{LOAD} = 10 pF		20	45	87	kHz
		A2 devices, C_{LOAD} = 10 pF		18	37	78	
		A3 devices, C_{LOAD} = 10 pF		16	35	73	
		A4 devices, C_{LOAD} = 10 pF		14	33	64	
		A5 devices, C_{LOAD} = 10 pF		9	27	44	
SR	Slew rate[2]	V_S = 5.0 V, V_{OUT} = 0.5 V to 4.5 V		0.1	0.3	1	V/µs
t_S	Settling time[2]	From current step to within 1% of final value		8	30	100	µs

at T_A = 25°C, $V_{SENSE} = V_{IN+} – V_{IN–}$, V_S = 1.8 V to 5.0 V, V_{IN+} = 12 V, $V_{REF} = V_S / 2$, and $V_{ENABLE} = V_S$ (unless otherwise noted)

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
NOISE, RTI(1)						
	Voltage noise density(2)		25	75	225	nV/√Hz
ENABLE						
I_{EN}	Leakage input current	0 V ≤ V_{ENABLE} ≤ V_S, T_A = –55°C to +150°C		1	100	nA
V_{IH}	High-level input voltage	T_A = –55°C to +150°C	0.7 × V_S		6	V
V_{IL}	Low-level input voltage	T_A = –55°C to +150°C	0		0.3 × V_S	V
V_{HYS}	Hysteresis			300		mV
I_{ODIS}	Output leakage disabled	V_S = 5.0 V, V_{OUT} = 0 V to 5.0 V, V_{ENABLE} = 0 V, T_A = –55°C to +150°C		1	5	µA
POWER SUPPLY						
I_Q	Quiescent current	V_S = 1.8 V, V_{SENSE} = 0 mV		48	65	µA
		V_S = 1.8 V, V_{SENSE} = 0 mV, T_A = –55°C to +150°C			90	
I_{QDIS}	Quiescent current disabled	V_{ENABLE} = 0 V, V_{SENSE} = 0 mV		10	100	nA
		V_{ENABLE} = 0 V, V_{SENSE} = 0 mV, T_A = –55°C to +150°C			500	

(1) RTI = referred-to-input.
(2) Specification based on statistical simulation results or characterization, not tested in final production.

6.6 Typical Characteristics

at T_A = 25°C, V_S = 1.8 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, V_{ENABLE} = V_S, and for all gain options (unless otherwise noted)

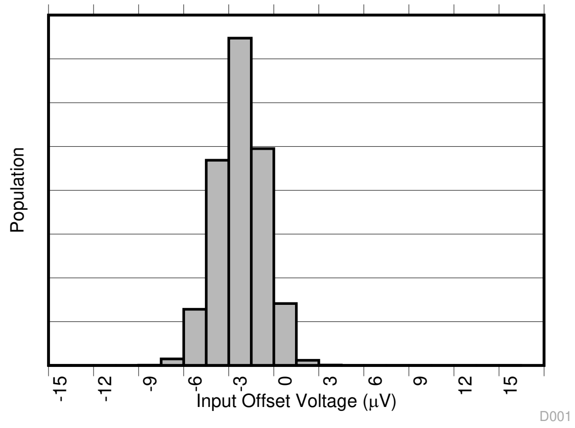


Figure 6-1. Input Offset Voltage Production Distribution

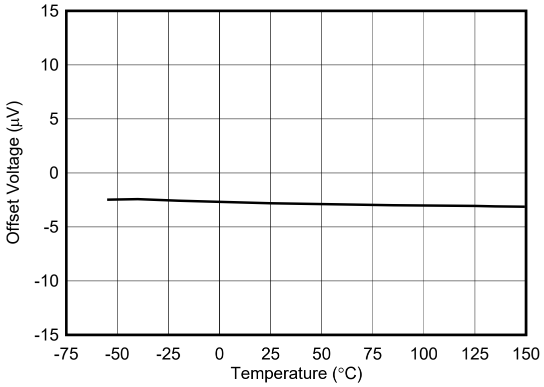


Figure 6-2. Offset Voltage vs. Temperature

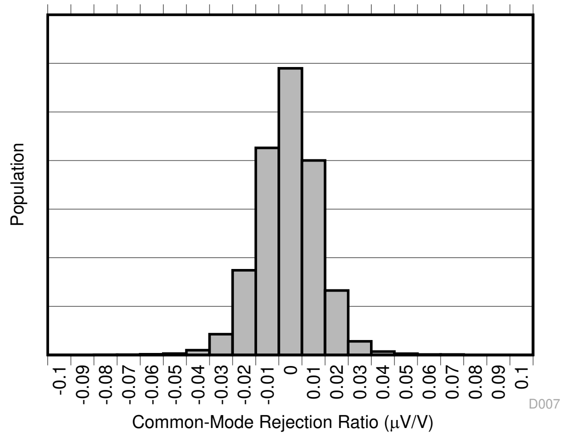


Figure 6-3. Common-Mode Rejection Production Distribution

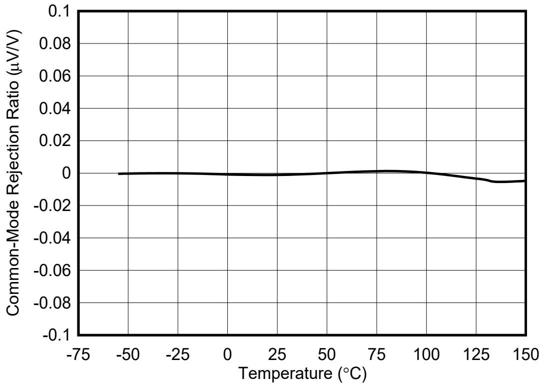
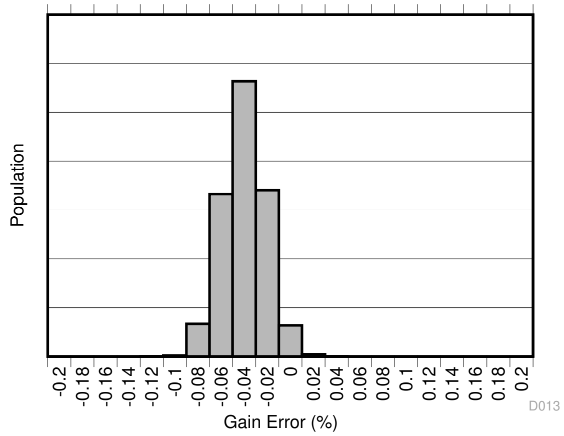
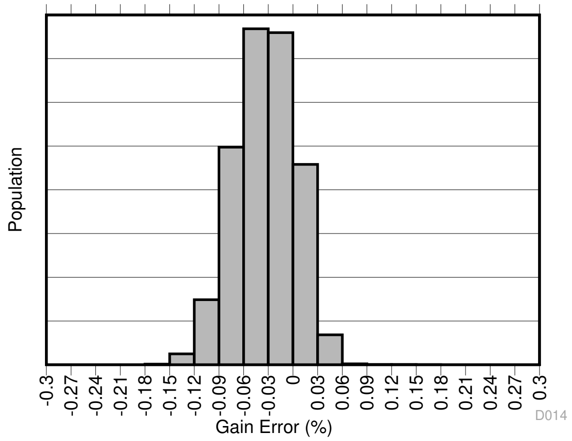


Figure 6-4. Common-Mode Rejection Ratio vs. Temperature



A1 devices

Figure 6-5. Gain Error Production Distribution



A2, A3, and A4 devices

Figure 6-6. Gain Error Production Distribution

6.6 Typical Characteristics (continued)

at T_A = 25°C, V_S = 1.8 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, V_{ENABLE} = V_S, and for all gain options (unless otherwise noted)

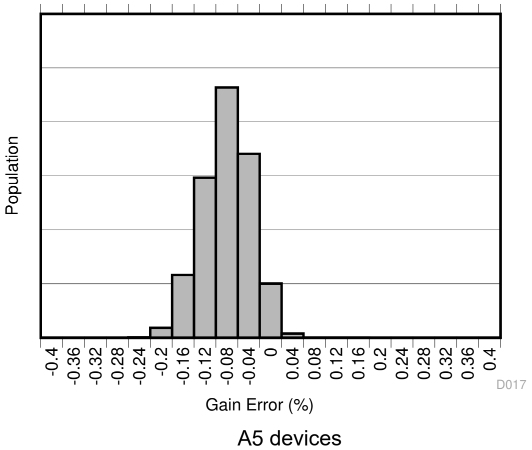


Figure 6-7. Gain Error Production Distribution

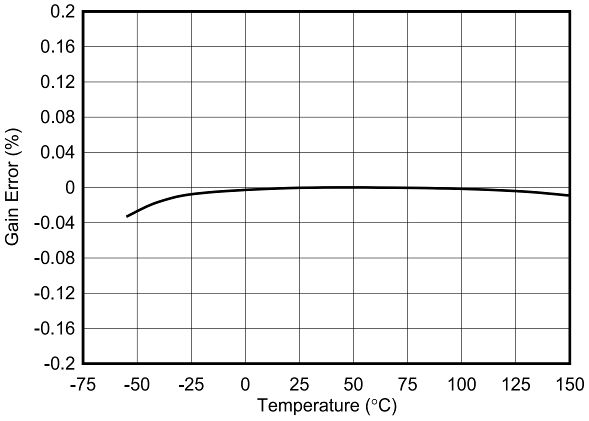


Figure 6-8. Gain Error vs. Temperature

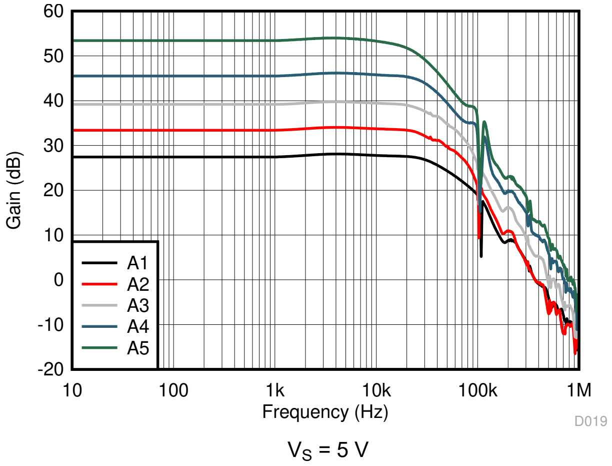


Figure 6-9. Gain vs. Frequency

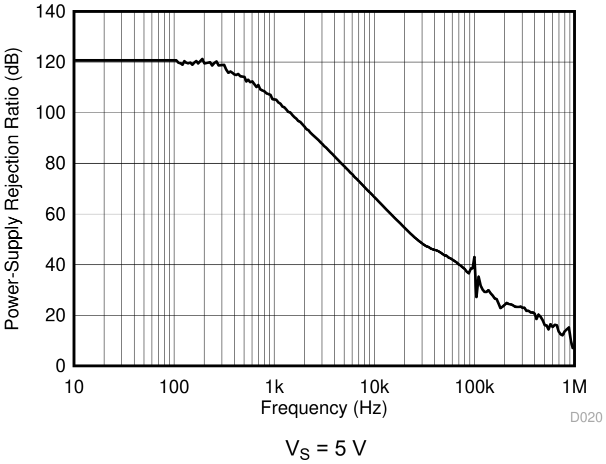


Figure 6-10. Power-Supply Rejection Ratio vs. Frequency

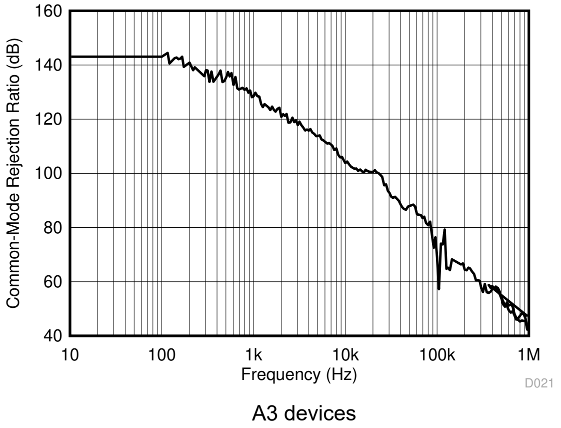


Figure 6-11. Common-Mode Rejection Ratio vs. Frequency

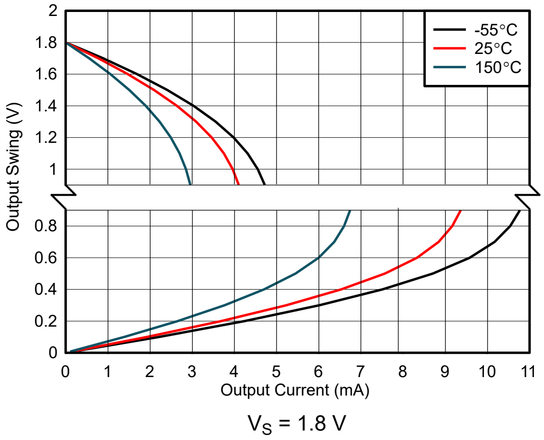
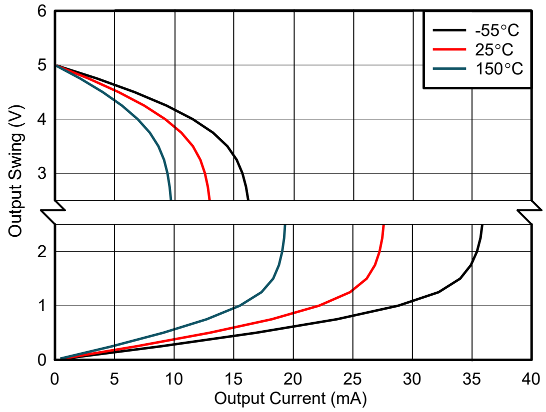


Figure 6-12. Output Voltage Swing vs. Output Current

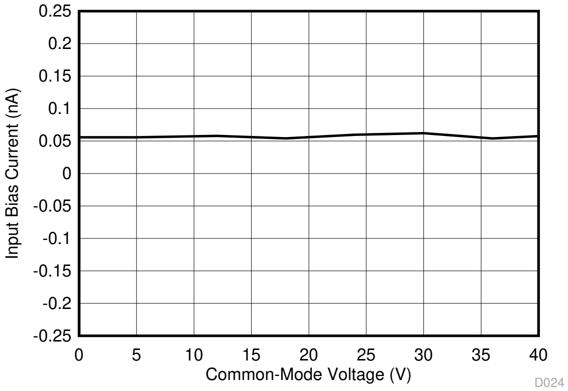
6.6 Typical Characteristics (continued)

at T_A = 25°C, V_S = 1.8 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, V_{ENABLE} = V_S, and for all gain options (unless otherwise noted)



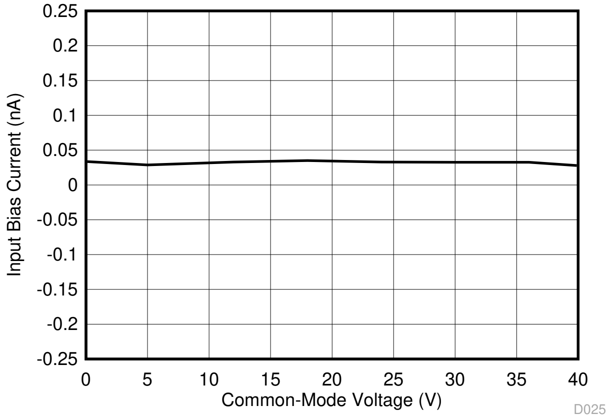
V_S = 5.0 V

Figure 6-13. Output Voltage Swing vs. Output Current



V_S = 5.0 V

Figure 6-14. Input Bias Current vs. Common-Mode Voltage



V_{ENABLE} = 0 V

Figure 6-15. Input Bias Current vs. Common-Mode Voltage (Shutdown)

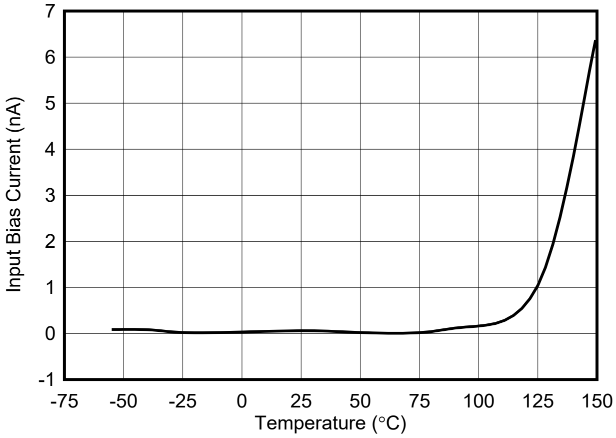


Figure 6-16. Input Bias Current vs. Temperature

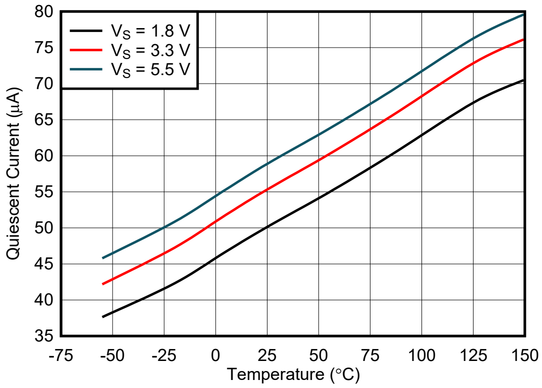
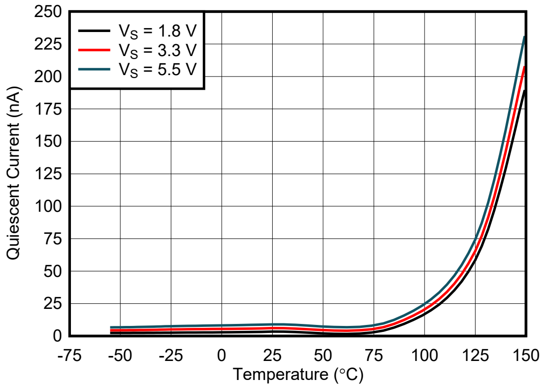


Figure 6-17. Quiescent Current vs. Temperature (Enabled)

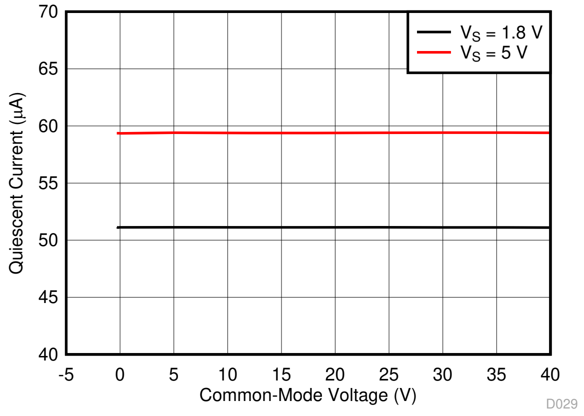


V_{ENABLE} = 0 V

Figure 6-18. Quiescent Current vs. Temperature (Disabled)

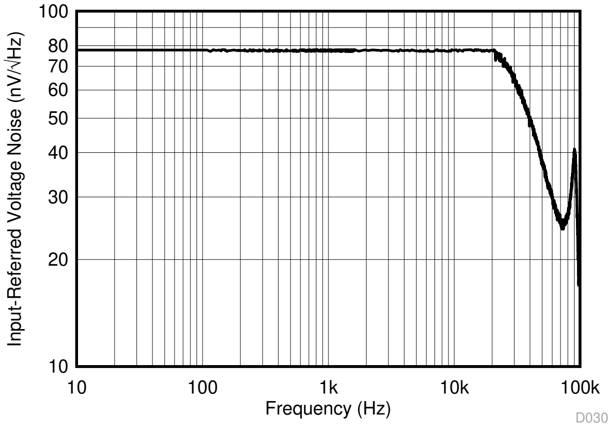
6.6 Typical Characteristics (continued)

at T_A = 25°C, V_S = 1.8 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, V_{ENABLE} = V_S, and for all gain options (unless otherwise noted)



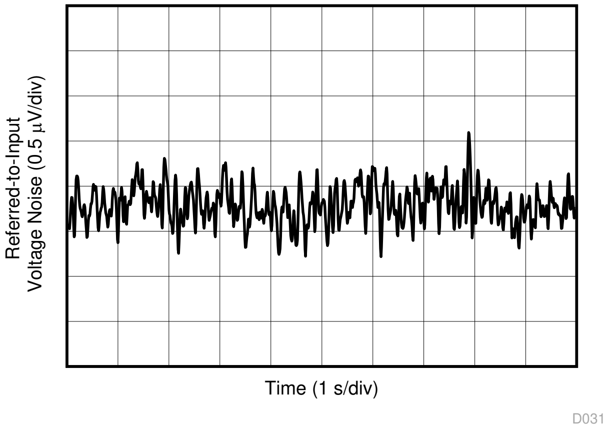
V_S = 5.0 V

Figure 6-19. Quiescent Current vs. Common-Mode Voltage



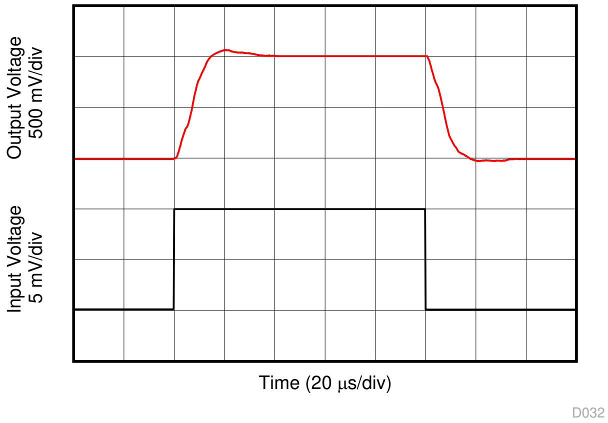
A3 devices

Figure 6-20. Input-Referred Voltage Noise vs. Frequency



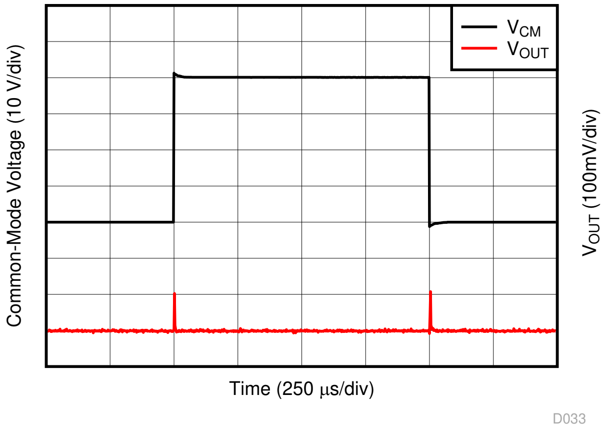
A3 devices

Figure 6-21. 0.1-Hz to 10-Hz Voltage Noise (Referred-To-Input)



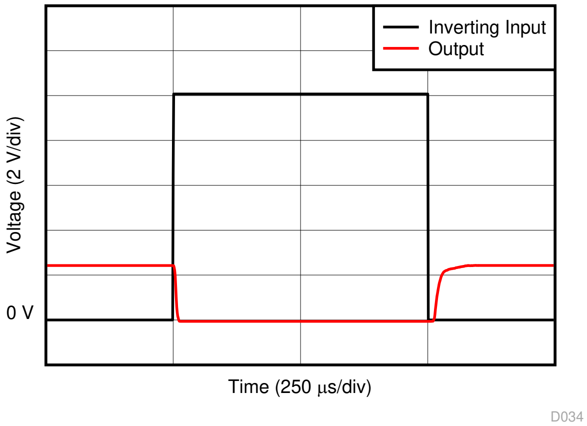
V_S = 5.0 V, A3 devices

Figure 6-22. Step Response (10-mV_{PP} Input Step)



A3 devices

Figure 6-23. Common-Mode Voltage Transient Response

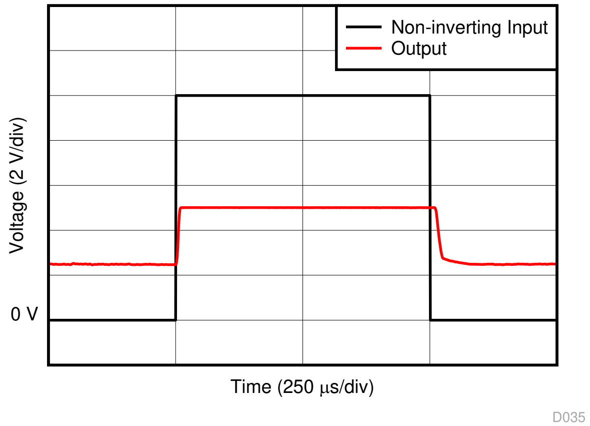


A3 devices

Figure 6-24. Inverting Differential Input Overload

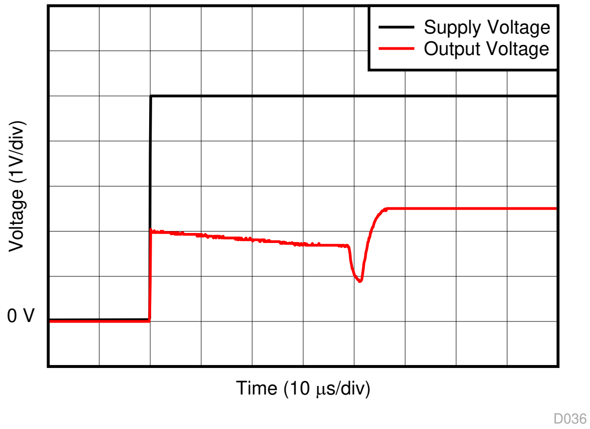
6.6 Typical Characteristics (continued)

at T_A = 25°C, V_S = 1.8 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, V_{ENABLE} = V_S, and for all gain options (unless otherwise noted)



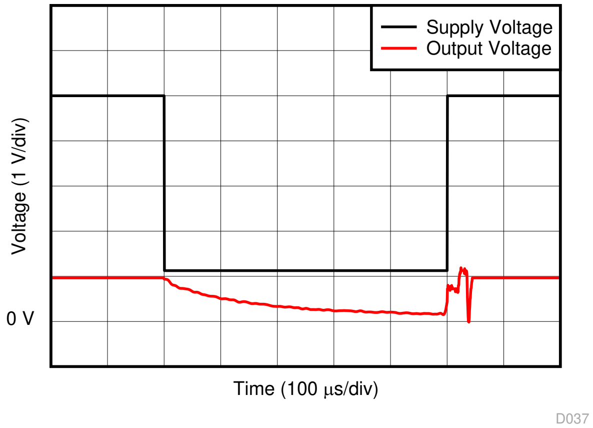
V_S = 5.0 V, A3 devices

Figure 6-25. Noninverting Differential Input Overload



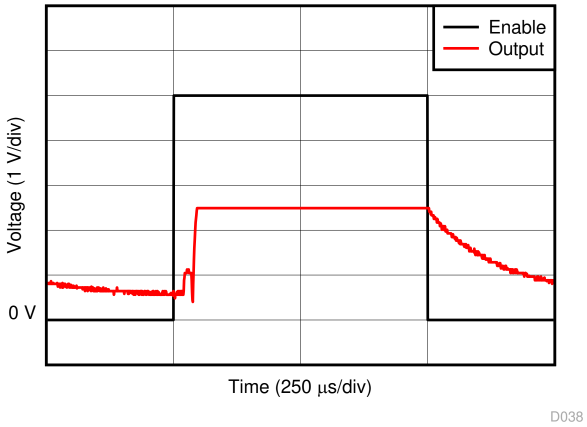
V_S = 5.0 V, A3 devices

Figure 6-26. Start-Up Response



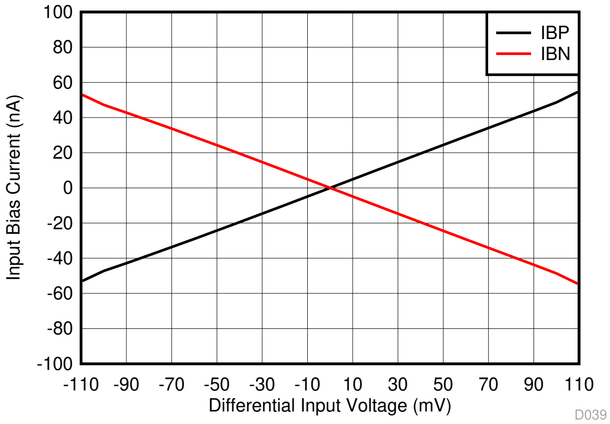
V_S = 5.0 V, A3 devices

Figure 6-27. Brownout Recovery



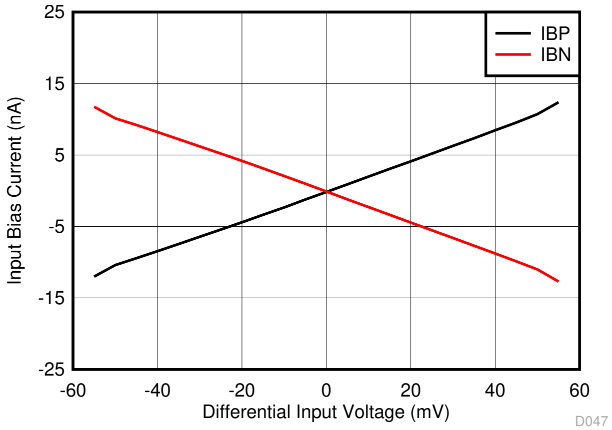
V_S = 5.0 V, A3 devices

Figure 6-28. Enable and Disable Response



V_S = 5.0 V, V_{REF} = 2.5 V, A1 devices

Figure 6-29. IB+ and IB– vs. Differential Input Voltage

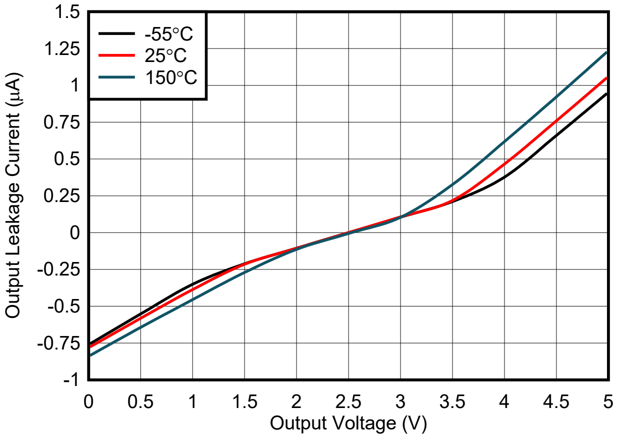


V_S = 5.0 V, V_{REF} = 2.5 V, A2, A3, A4, A5 devices

Figure 6-30. IB+ and IB– vs. Differential Input Voltage

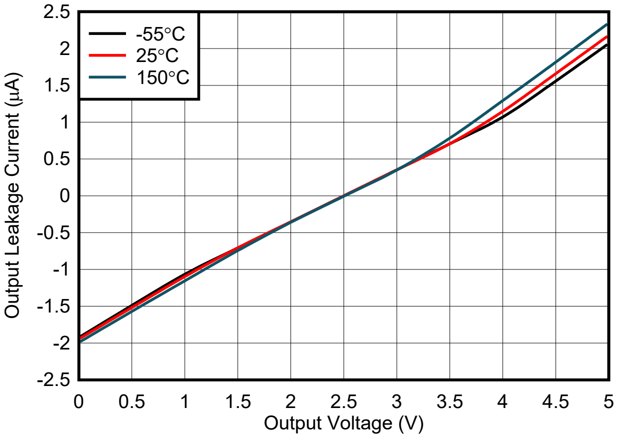
6.6 Typical Characteristics (continued)

at T_A = 25°C, V_S = 1.8 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, V_{ENABLE} = V_S, and for all gain options (unless otherwise noted)



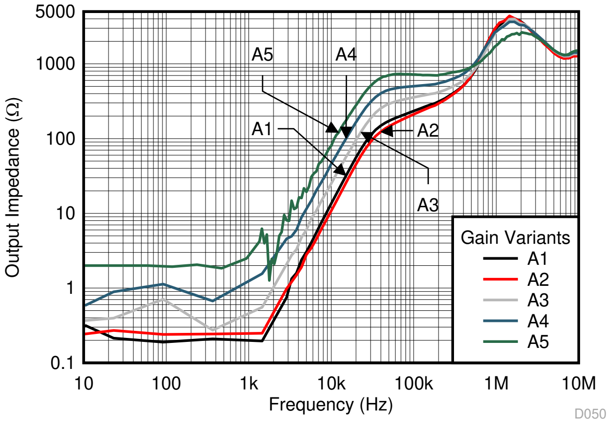
V_S = 5.0 V, V_{ENABLE} = 0 V, V_{REF} = 2.5 V

Figure 6-31. Output Leakage vs. Output Voltage (A1, A2, and A3 Devices)



V_S = 5.0 V, V_{ENABLE} = 0 V, V_{REF} = 2.5 V

Figure 6-32. Output Leakage vs. Output Voltage (A4 and A5 Devices)



V_S = 5.0 V, V_{CM} = 0 V

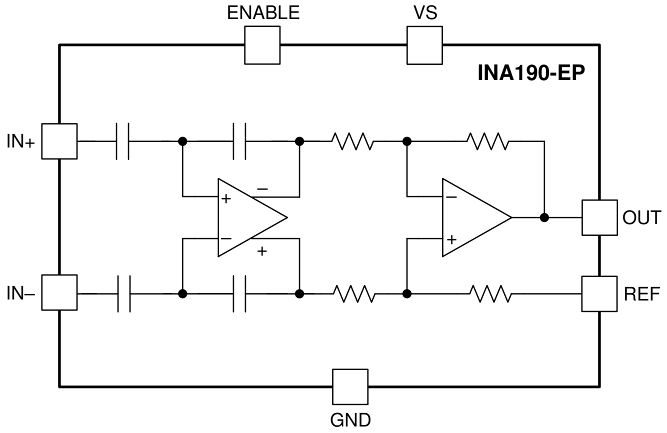
Figure 6-33. Output Impedance vs. Frequency

7 Detailed Description

7.1 Overview

The INA190-EP is a low bias current, low offset, 40-V common-mode, current-sensing amplifier with an enable pin. The INA190-EP is a specially designed, current-sensing amplifier that accurately measures voltages developed across current-sensing resistors on common-mode voltages that far exceed the supply voltage. Current is measured on input voltage rails as high as 40 V at V_{IN+} and $V_{IN–}$, with a supply voltage, V_S, as low as 1.7 V. When disabled, the output goes to a high-impedance state, and the supply current draw is reduced to less than 0.1 µA. The INA190-EP is intended for use in both low-side and high-side current-sensing configurations where high accuracy and low current consumption are required.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Precision Current Measurement

The INA190-EP allows for accurate current measurements over a wide dynamic range. The high accuracy of the device is attributable to the low gain error and offset specifications. The offset voltage of the INA190-EP is less than 15 μV. In this case, the low offset improves the accuracy at light loads when V_{IN+} approaches V_{IN-}. Another advantage of low offset is the ability to use a lower-value shunt resistor that reduces the power loss in the current-sense circuit, and improves the power efficiency of the end application.

The maximum gain error of the INA190-EP is specified between 0.2% and 0.4% of the actual value, depending on the gain option. As the sensed voltage becomes much larger than the offset voltage, the gain error becomes the dominant source of error in the current-sense measurement. When the device monitors currents near the full-scale output range, the total measurement error approaches the value of the gain error.

7.3.2 Low Input Bias Current

The INA190-EP is different from many current-sense amplifiers because this device offers very low input bias current. The low input bias current of the INA190-EP has three primary benefits.

The first benefit is the reduction of the current consumed by the device in both the enabled and disabled states. Classical current-sense amplifier topologies typically consume tens of microamps of current at the inputs. For these amplifiers, the input current is the result of the resistor network that sets the gain and additional current to bias the input amplifier. To reduce the bias current to near zero, the INA190-EP uses a capacitively coupled amplifier on the input stage, followed by a difference amplifier on the output stage.

The second benefit of low bias current is the ability to use input filters to reject high-frequency noise before the signal is amplified. In a traditional current-sense amplifier, the addition of input filters comes at the cost of reduced accuracy. However, as a result of the low bias currents, input filters have little effect on the measurement accuracy of the INA190-EP.

The third benefit of low bias current is the ability to use a larger current-sense resistor. This ability allows the device to accurately monitor currents as low as 1 μA.

7.3.3 Low Quiescent Current With Output Enable

The device features low quiescent current (I_Q), while still providing sufficient small-signal bandwidth to be usable in most applications. The quiescent current of the INA190-EP is only 48 μA (typ), while providing a small-signal bandwidth of 35 kHz in a gain of 100. The low I_Q and good bandwidth allow the device to be used in many portable electronic systems without excessive drain on the battery. Because many applications only need to periodically monitor current, the INA190-EP features an enable pin that turns off the device until needed. When in the disabled state, the INA190-EP typically draws 10 nA of total supply current.

7.3.4 Bidirectional Current Monitoring

INA190-EP devices can sense current flow through a sense resistor in both directions. The bidirectional current-sensing capability is achieved by applying a voltage at the REF pin to offset the output voltage. A positive differential voltage sensed at the inputs results in an output voltage that is greater than the applied reference voltage. Likewise, a negative differential voltage at the inputs results in output voltage that is less than the applied reference voltage. Use Equation 1 to calculate the output voltage of the current-sense amplifier.

$$V_{OUT} = \left(I_{LOAD} \times R_{SENSE} \times GAIN\right) + V_{REF} \tag{1}$$

where

- I_{LOAD} is the load current to be monitored.
- R_{SENSE} is the current-sense resistor.
- GAIN is the gain option of the selected device.
- V_{REF} is the voltage applied to the REF pin.

7.3.5 High-Side and Low-Side Current Sensing

The INA190-EP supports input common-mode voltages from –0.2 V to +40 V. Because of the internal topology, the common-mode range is not restricted by the power-supply voltage (V_S). The ability to operate with common-mode voltages greater or less than V_S allows the INA190-EP to be used in high-side and low-side current-sensing applications (see Figure 7-1).

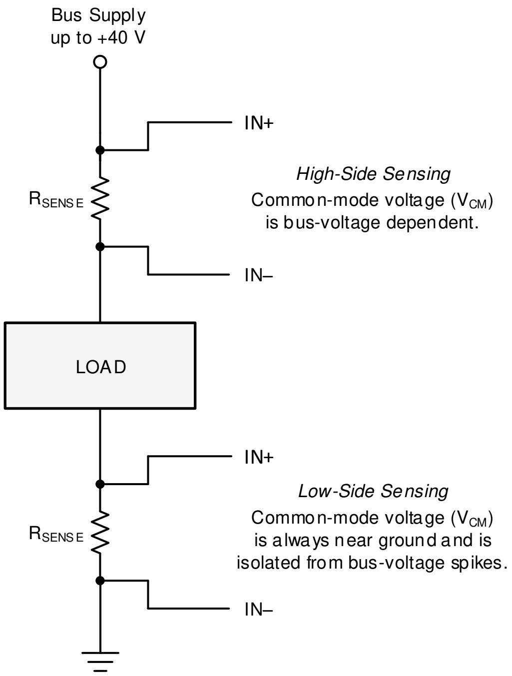


Figure 7-1. High-Side and Low-Side Sensing Connections

7.3.6 High Common-Mode Rejection

The INA190-EP uses a capacitively coupled amplifier on the front end. Therefore, DC common-mode voltages are blocked from downstream circuits, resulting in very high common-mode rejection. Typically, the common-mode rejection of the INA190-EP is approximately 150 dB. The ability to reject changes in the DC common-mode voltage allows the INA190-EP to monitor both high- and low-voltage rail currents with very little change in the offset voltage.

7.3.7 Rail-to-Rail Output Swing

The INA190-EP allows linear current-sensing operation with the output close to the supply rail and ground. The maximum specified output swing to the positive rail is V_S – 40 mV, and the maximum specified output swing to GND is only GND + 1 mV. The close-to-rail output swing is useful to maximize the usable output range, particularly when operating the device from a 1.8-V supply.

7.4 Device Functional Modes

7.4.1 Normal Operation

The INA190-EP is in normal operation when the following conditions are met:

- The power-supply voltage (V_S) is between 1.7 V and 5.5 V.
- The common-mode voltage (V_{CM}) is within the specified range of –0.2 V to +40 V.
- The maximum differential input signal times the gain plus V_{REF} is less than the positive swing voltage V_{SP}.
- The ENABLE pin is driven or connected to V_S.
- The minimum differential input signal times the gain plus V_{REF} is greater than the zero load swing to GND, V_{ZL} (see the *Rail-to-Rail Output Swing* section).

During normal operation, this device produces an output voltage that is the *amplified* representation of the difference voltage from IN+ to IN– plus the voltage applied to the REF pin.

7.4.2 Unidirectional Mode

This device can be configured to monitor current flowing in one direction (unidirectional) or in both directions (bidirectional) depending on how the REF pin is connected. Figure 7-2 shows the device operating in unidirectional mode where the output is near ground when no current is flowing. When the current flows from the bus supply to the load, the input voltage from IN+ to IN– increases and causes the output voltage at the OUT pin to increase.

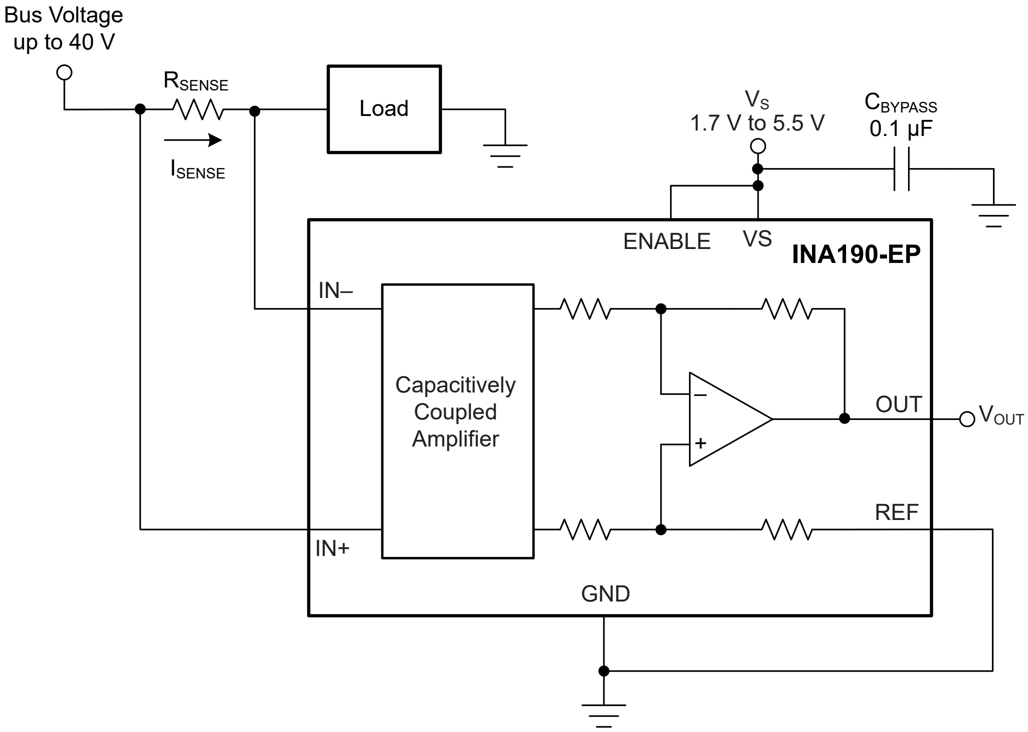


Figure 7-2. Typical Unidirectional Application

The linear range of the output stage is limited by how close the output voltage can approach ground under zero input conditions. The zero current output voltage of the INA190-EP is very small and for most unidirectional applications the REF pin is simply grounded. However, if the measured current multiplied by the current sense resistor and device gain is less than the zero current output voltage, then bias the REF pin to a convenient value above the zero current output voltage to get the output into the linear range of the device. To limit common-mode rejection errors, buffer the reference voltage connected to the REF pin.

A less-frequently used output biasing method is to connect the REF pin to the power-supply voltage, V_S. This method results in the output voltage saturating at 40 mV less than the supply voltage when no differential input voltage is present. This method is similar to the output saturated low condition with no differential input voltage when the REF pin is connected to ground. The output voltage in this configuration only responds to currents that develop negative differential input voltage relative to the device IN– pin. Under these conditions, when the negative differential input signal increases, the output voltage moves downward from the saturated supply voltage. The voltage applied to the REF pin must not exceed V_S.

Another use for the REF pin in unidirectional operation is to level shift the output voltage. Figure 7-3 shows an application where the device ground is set to a negative voltage so currents biased to negative supplies, as seen in optical networking cards, can be measured. The GND of the INA190-EP can be set to negative voltages, as long as the inputs do not violate the common-mode range specification and the voltage difference between VS and GND does not exceed 5.5 V. In this example, the output of the INA190-EP is fed into a positive-biased ADC. By grounding the REF pin, the voltages at the output will be positive and not damage the ADC. To make sure the output voltage never goes negative, the supply sequencing must be the positive supply first, followed by the negative supply.

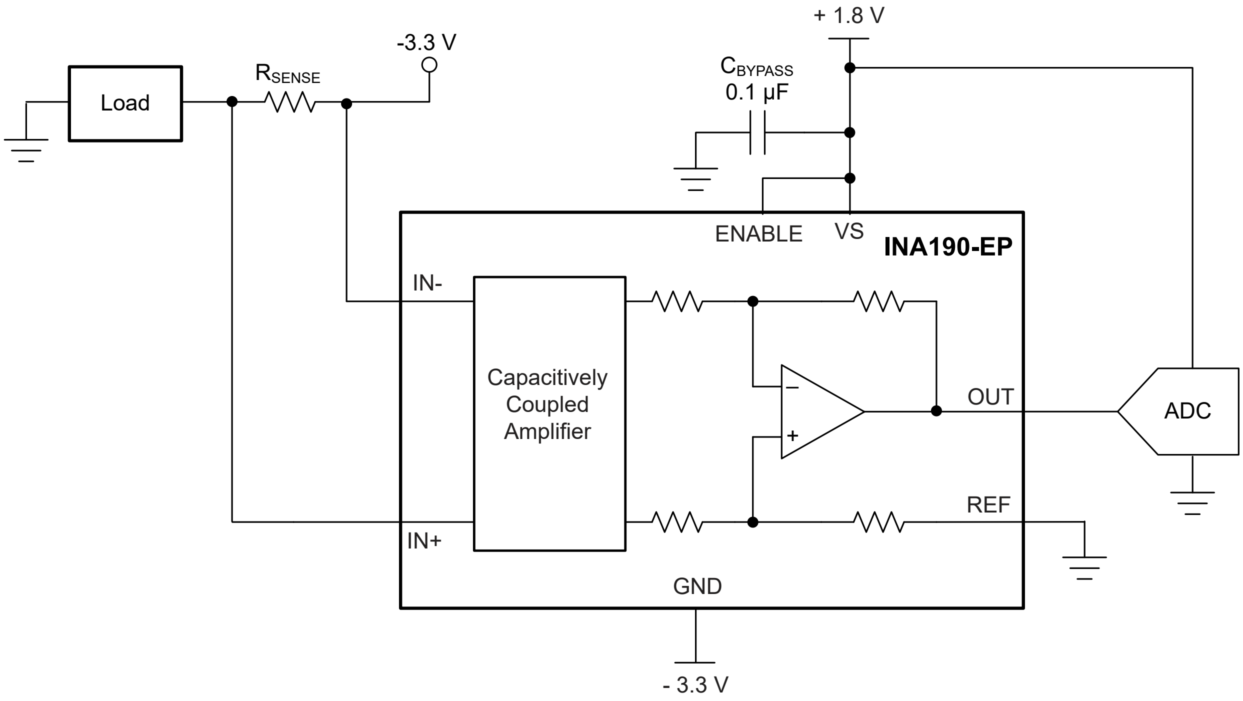


Figure 7-3. Using the REF Pin to Level-Shift Output Voltage

7.4.3 Bidirectional Mode

The INA190-EP devices are bidirectional current-sense amplifiers capable of measuring currents through a resistive shunt in two directions. This bidirectional monitoring is common in applications that include charging and discharging operations where the current flowing through the resistor can change directions.

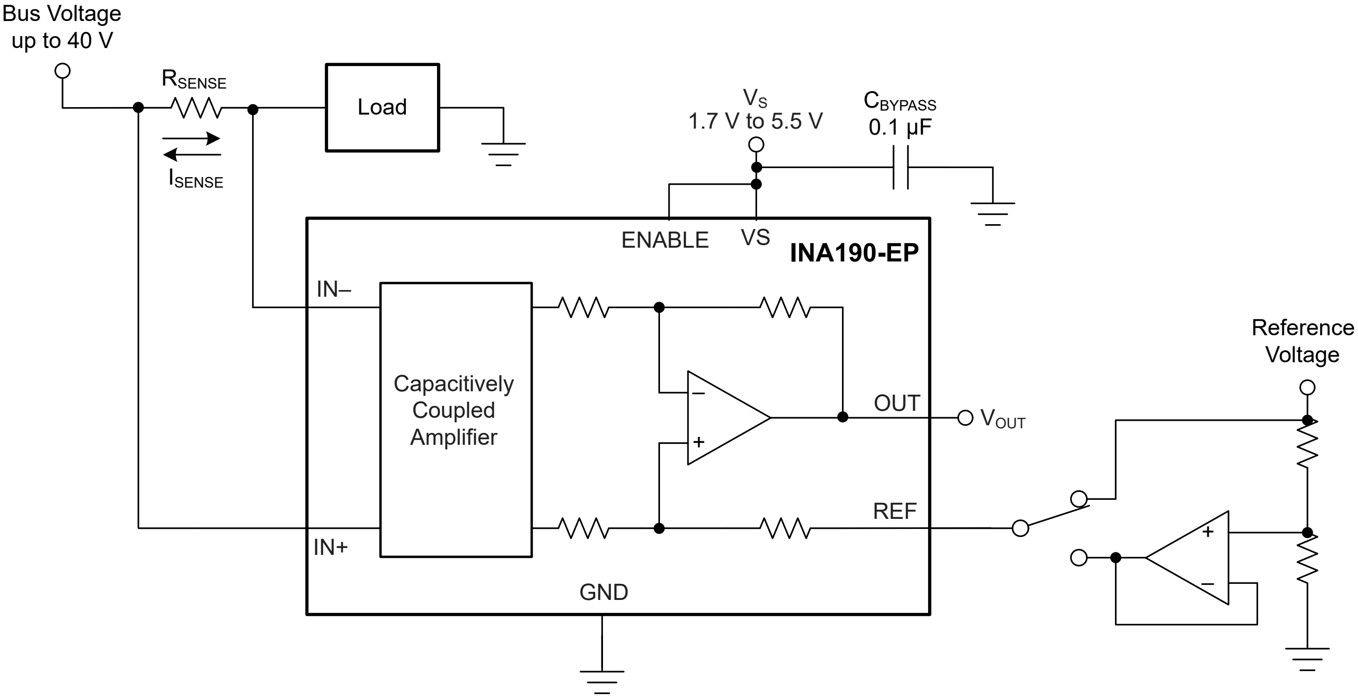


Figure 7-4. Bidirectional Application

The user can apply a voltage to the REF pin to measure this current flowing in both directions (see Figure 7-4). The voltage applied to REF (V_{REF}) sets the output state that corresponds to the zero-input level state. The output then responds by increasing above V_{REF} for positive differential signals (relative to the IN– pin) and responds by decreasing below V_{REF} for negative differential signals. This reference voltage applied to the REF pin can be set anywhere between 0 V to V_S. For bidirectional applications, V_{REF} is typically set at $V_S/2$ for equal signal range in both current directions. In some cases, V_{REF} is set at a voltage other than $V_S/2$; for example, when the bidirectional current and corresponding output signal do not need to be symmetrical.

7.4.4 Input Differential Overload

If the differential input voltage ($V_{IN+} - V_{IN-}$) times gain exceeds the voltage swing specification, the INA190-EP drives its output as close as possible to the positive supply or ground, and does not provide accurate measurement of the differential input voltage. If this input overload occurs during normal circuit operation, then reduce the value of the shunt resistor or use a lower-gain version with the chosen sense resistor to avoid this mode of operation. If a differential overload occurs in a time-limited fault event, then the output of the INA190-EP returns to the expected value approximately 80 µs after the fault condition is removed.

7.4.5 Shutdown

Specific package options of the INA190-EP feature an active-high ENABLE pin that shuts down the device when pulled to ground. When the device is shut down, the quiescent current is reduced to 10 nA (typical), and the output goes to a high-impedance state. In a battery-powered application, the low quiescent current extends the battery lifetime when the current measurement is not needed. When the ENABLE pin is driven to the supply voltage, the device turns back on. The typical output settling time when enabled is 130 μs.

The output of the INA190-EP goes to a high-impedance state when disabled. Therefore, you can connect multiple outputs of the INA190-EP together to a single ADC or measurement device (see Figure 7-5).

When connected in this way, enable only one INA190-EP at a time, and make sure all devices have the same supply voltage.

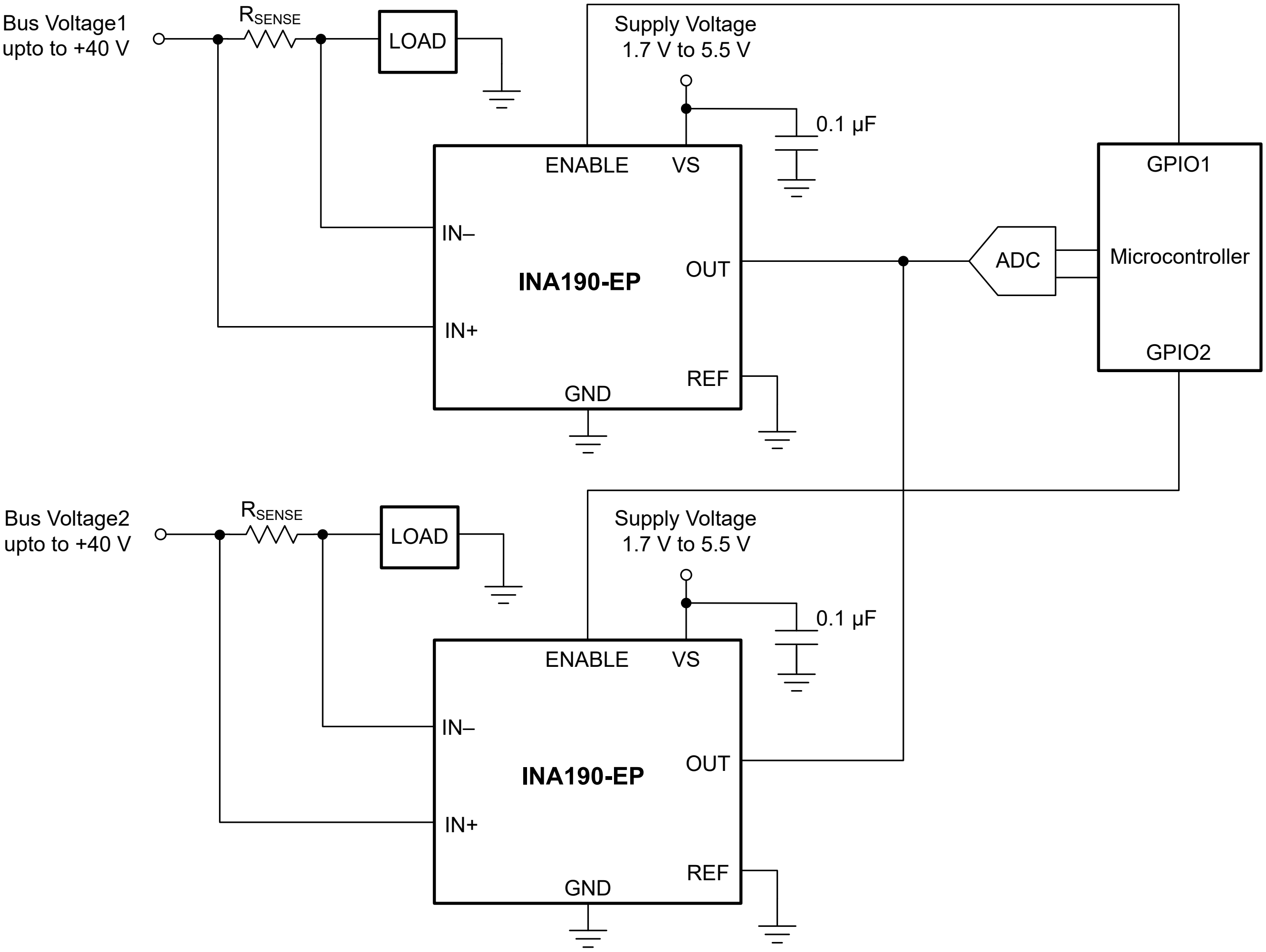


Figure 7-5. Multiplexing Multiple Devices With the ENABLE Pin

8 Application and Implementation

Note

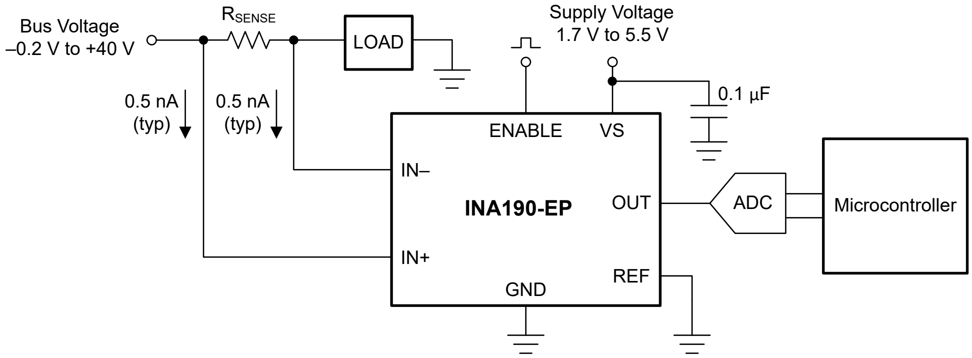
Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes, as well as validating and testing their design implementation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

8.1 Application Information

The INA190-EP amplifies the voltage developed across a current-sensing resistor as current flows through the resistor to the load or ground. The high common-mode rejection of the INA190-EP make it usable over a wide range of voltage rails while still maintaining an accurate current measurement.

8.1.1 Basic Connections

Figure 8-1 shows the basic connections of the INA190-EP. Place the device as close as possible to the current sense resistor and connect the input pins (IN+ and IN–) to the current sense resistor through kelvin connections.If present, the ENABLE pin must be controlled externally or connected to VS if not used.



NOTE: To help eliminate ground offset errors between the device and the analog-to-digital converter (ADC), connect the REF pin to the ADC reference input. When driving SAR ADCs, filter or buffer the output of the INA190-EP before connecting directly to the ADC.

Figure 8-1. Basic Connections for the INA190-EP

8.1.2 R_{SENSE} and Device Gain Selection

The accuracy of any current-sense amplifier is maximized by choosing the current-sense resistor to be as large as possible. A large sense resistor maximizes the differential input signal for a given amount of current flow and reduces the error contribution of the offset voltage. However, there are practical limits as to how large the current-sense resistor can be in a given application because of the resistor size and maximum allowable power dissipation. Equation 2 gives the maximum value for the current-sense resistor for a given power dissipation budget:

$$R_{SENSE} < \frac{PD_{MAX}}{I_{MAX}^2} \tag{2}$$

where:

- PD_{MAX} is the maximum allowable power dissipation in R_{SENSE}.
- I_{MAX} is the maximum current that will flow through R_{SENSE}.

An additional limitation on the size of the current-sense resistor and device gain is due to the power-supply voltage, V_S, and device swing-to-rail limitations. In order to make sure that the current-sense signal is properly passed to the output, both positive and negative output swing limitations must be examined. Equation 3 provides the maximum values of R_{SENSE} and GAIN to keep the device from exceeding the positive swing limitation.

$$I_{MAX} \times R_{SENSE} \times GAIN < V_{SP} - V_{REF} \tag{3}$$

where:

- I_{MAX} is the maximum current that will flow through R_{SENSE}.
- GAIN is the gain of the current-sense amplifier.
- V_{SP} is the positive output swing as specified in the data sheet.
- V_{REF} is the externally applied voltage on the REF pin.

To avoid positive output swing limitations when selecting the value of R_{SENSE}, there is always a trade-off between the value of the sense resistor and the gain of the device under consideration. If the sense resistor selected for the maximum power dissipation is too large, then it is possible to select a lower-gain device in order to avoid positive swing limitations.

The negative swing limitation places a limit on how small the sense resistor value can be for a given application. Equation 4 provides the limit on the minimum value of the sense resistor.

$$I_{MIN} \times R_{SENSE} \times GAIN > V_{SN} - V_{REF} \tag{4}$$

where:

- I_{MIN} is the minimum current that will flow through R_{SENSE}.
- GAIN is the gain of the current-sense amplifier.
- V_{SN} is the negative output swing of the device (see *Rail-to-Rail Output Swing*).
- V_{REF} is the externally applied voltage on the REF pin.

In addition to adjusting R_{SENSE} and the device gain, the voltage applied to the REF pin can be slightly increased above GND to avoid negative swing limitations.

8.1.3 Signal Conditioning

When performing accurate current measurements in noisy environments, the current-sensing signal is often filtered. The INA190-EP features low input bias currents. Therefore, adding a differential mode filter to the input without sacrificing the current-sense accuracy is possible. Filtering at the input is advantageous because this action attenuates differential noise before the signal is amplified. Figure 8-2 provides an example of how to use a filter on the input pins of the device.

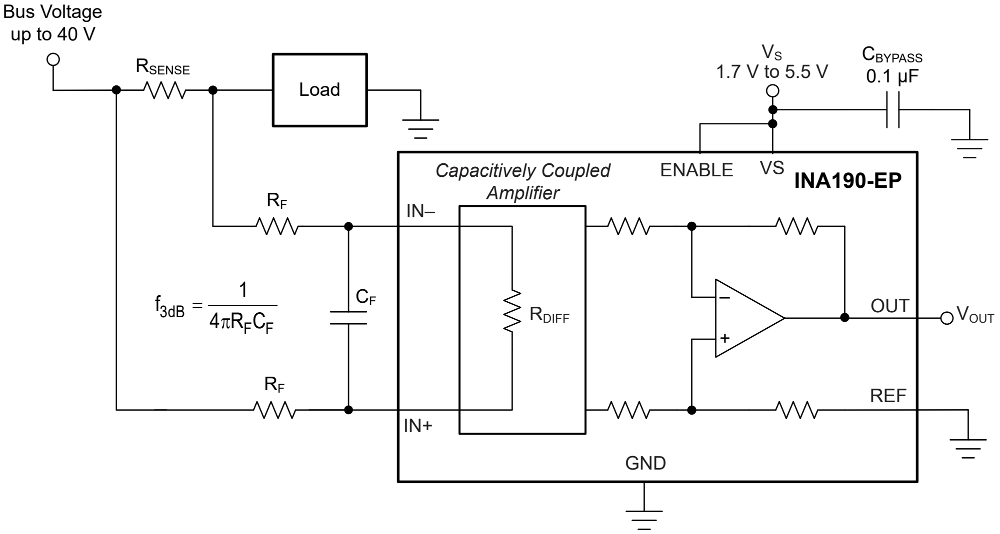


Figure 8-2. Filter at the Input Pins

Figure 8-3 shows the value of R_{DIFF} as a function of the device temperature.

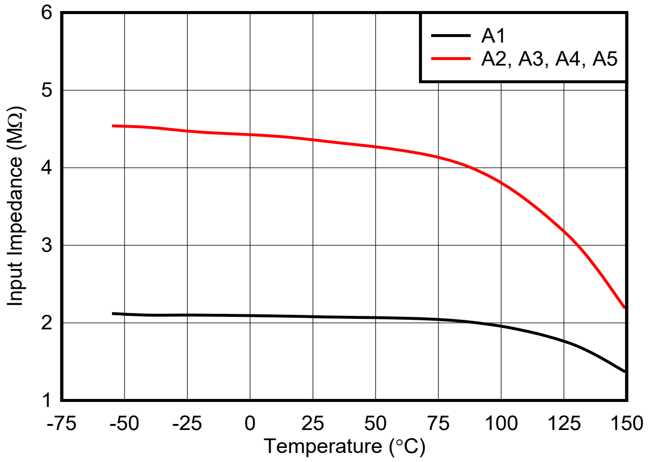


Figure 8-3. Differential Input Impedance vs. Temperature

As the voltage drop across the sense resistor (V_{SENSE}) increases, the amount of voltage dropped across the input filter resistors (R_F) also increases. The increased voltage drop results in additional gain error. Use Equation 5 to calculate the error caused by these resistors.

$$\text{Error}(\%) = \left(1 - \frac{R_{DIFF}}{R_{SENSE} + R_{DIFF} + (2 \times R_F)}\right) \times 100 \tag{5}$$

where:

- R_{DIFF} is the differential input impedance.
- R_F is the added value of the series filter resistance.

The input stage of the INA190-EP uses a capacitive feedback amplifier topology to achieve high dc precision. As a result, periodic high-frequency shunt voltage (or current) transients of significant amplitude (10 mV or greater) and duration (hundreds of nanoseconds or greater) may be amplified by the INA190-EP, even though the transients are greater than the device bandwidth. Use a differential input filter in these applications to minimize disturbances at the INA190-EP output.

The high input impedance and low bias current of the INA190-EP provide flexibility in the input filter design without impacting the accuracy of current measurement. For example, set R_F = 100 Ω and C_F = 22 nF to achieve a low-pass filter corner frequency of 36.2 kHz. These filter values significantly attenuate most unwanted high-frequency signals at the input without severely impacting the current-sensing bandwidth or precision. If a lower corner frequency is desired, increase the value of C_F.

Filtering the input filters out differential noise across the sense resistor. If high-frequency, common-mode noise is a concern, add an RC filter from the OUT pin to ground. The RC filter helps filter out both differential and common-mode noise, as well as internally generated noise from the device. The value for the resistance of the RC filter is limited by the impedance of the load. Any current drawn by the load manifests as an external voltage drop from the INA190-EP OUT pin to the load input. To select the optimal values for the output filter, use Figure 6-33 and see the *Closed-Loop Analysis of Load-Induced Amplifier Stability Issues Using ZOUT* application report

8.1.4 Common-Mode Voltage Transients

With a small amount of additional circuitry, the INA190-EP can be used in circuits subject to transients that exceed the absolute maximum voltage ratings. The most simple way to protect the inputs from negative transients is to add resistors in series to the IN– and IN+ pins. Use resistors that are 1 kΩ or less, and limit the current in the ESD structures to less than 5 mA. For example, using 1-kΩ resistors in series with the INA190-EP allows voltages as low as –5 V, while limiting the ESD current to less than 5 mA. If protection from high-voltage or more-negative, common-voltage transients is needed, use the circuits shown in Figure 8-4 and Figure 8-5. When implementing these circuits, 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 a working impedance for the Zener diode (see Figure 8-4). Keep these resistors as small as possible; most often, use around 100 Ω. Larger values can be used with an effect on gain that is discussed in the *Signal Conditioning* section. This circuit limits only short-term transients; therefore, many applications are satisfied with a 100-Ω resistor along with conventional Zener diodes of the lowest acceptable power rating. This combination uses the least amount of board space. These diodes can be found in packages as small as SOT-523 or SOD-523.

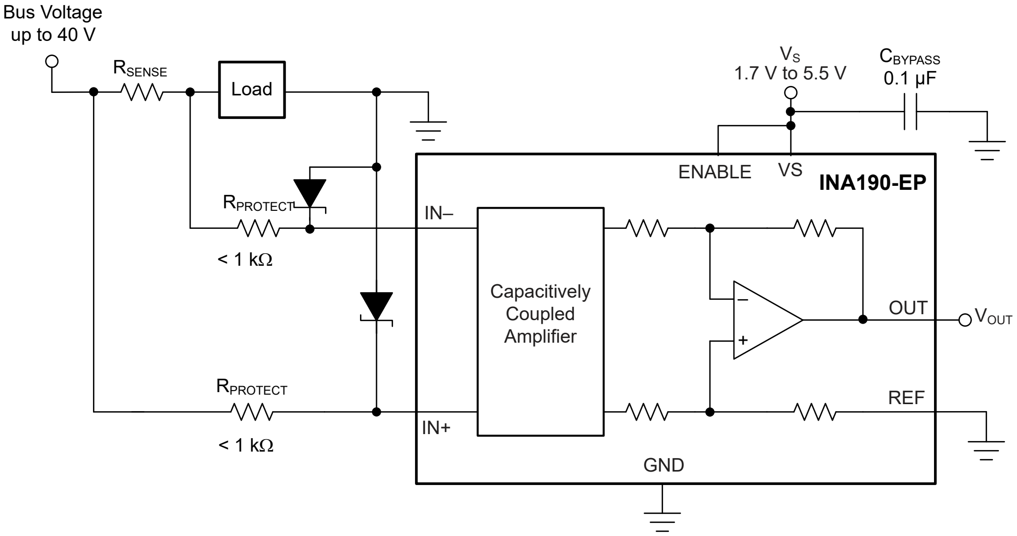


Figure 8-4. Transient Protection Using Dual Zener Diodes

In the event that low-power Zener diodes do not have sufficient transient absorption capability, a higher-power transzorb must be used. The most package-efficient solution involves using a single transzorb and back-to-back diodes between the device inputs (see Figure 8-5). The most space-efficient solutions are dual, series-connected diodes in a single SOT-523 or SOD-523 package. In either of the examples shown in Figure 8-4 and Figure 8-5, the total board area required by the INA190-EP with all protective components is less than that of an SO-8 package, and only slightly greater than that of an VSSOP-8 package.

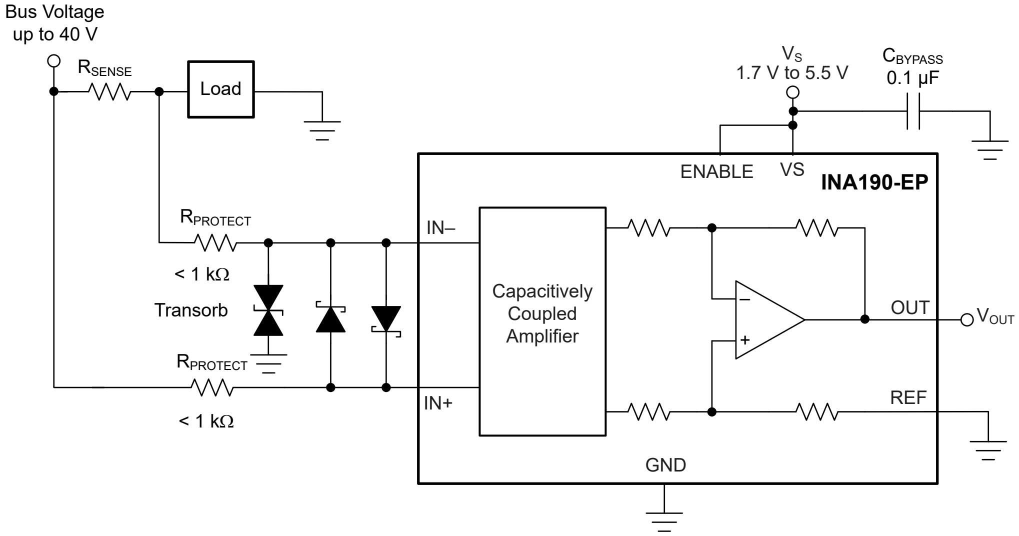


Figure 8-5. Transient Protection Using a Single Transzorb and Input Clamps

For more information, see the *Current Shunt Monitor With Transient Robustness* reference design.

8.2 Typical Applications

The low input bias current of the INA190-EP allows accurate monitoring of small-value currents. To accurately monitor currents in the microamp range, increase the value of the sense resistor to increase the sense voltage so that the error introduced by the offset voltage is small. Figure 8-6 shows the circuit configuration for monitoring low-value currents. As a result of the differential input impedance of the INA190-EP, limit the value of R_{SENSE} to 1 kΩ or less for best accuracy.

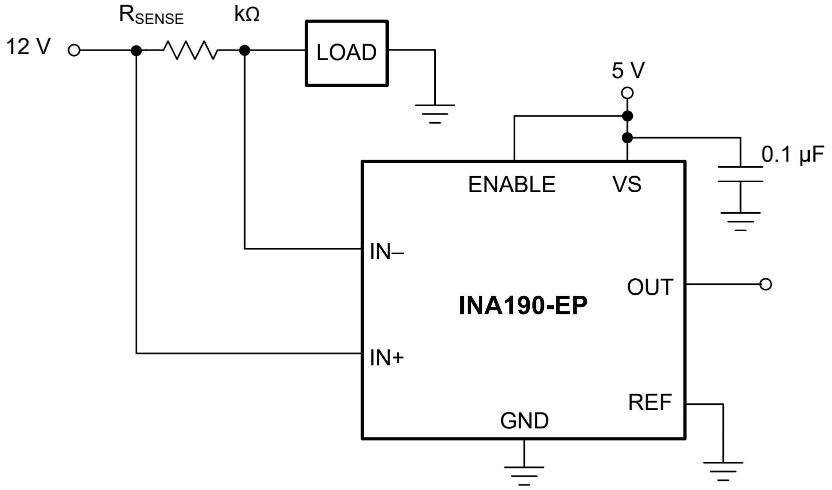


Figure 8-6. Microamp Current Measurement

8.2.1 Design Requirements

Table 8-1 lists the design requirements for the circuit shown in Figure 8-6.

Table 8-1. Design Parameters

DESIGN PARAMETER	EXAMPLE VALUE
Power-supply voltage (V_S)	5 V
Bus supply rail (V_{CM})	12 V
Minimum sense current (I_{MIN})	1 µA
Maximum sense current (I_{MAX})	150 µA
Device gain (GAIN)	25 V/V
Reference voltage (V_{REF})	0 V
Amplifier current in sleep or disabled state	< 1 µA

8.2.2 Detailed Design Procedure

The maximum value of the current-sense resistor is calculated based choice of gain, value of the maximum current the be sensed (I_{MAX}), and the power supply voltage(V_S). When operating at the maximum current, the output voltage must not exceed the positive output swing specification, V_{SP}. For the given design parameters, Equation 6 determines that the maximum value for R_{SENSE} is 1.321 kΩ.

$$R_{SENSE} < \frac{V_{SP}}{I_{MAX} \times GAIN} \tag{6}$$

However, because this value exceeds the maximum recommended value for R_{SENSE}, a resistance value of 1 kΩ must be used. When operating at the minimum current value, I_{MIN} the output voltage must be greater than the swing to GND (V_{SN}), specification. For this example, Equation 7 determines that the output voltage at the minimum current is 25 mV, which is greater than the value for V_{SN}.

$$V_{OUTMIN} = I_{MIN} \times R_{SENSE} \times GAIN \tag{7}$$

8.2.3 Application Curve

Figure 8-7 shows the output of the device when disabled and enabled while measuring a 40-µA load current. When disabled, the current draw from the device supply and inputs is less than 106 nA.

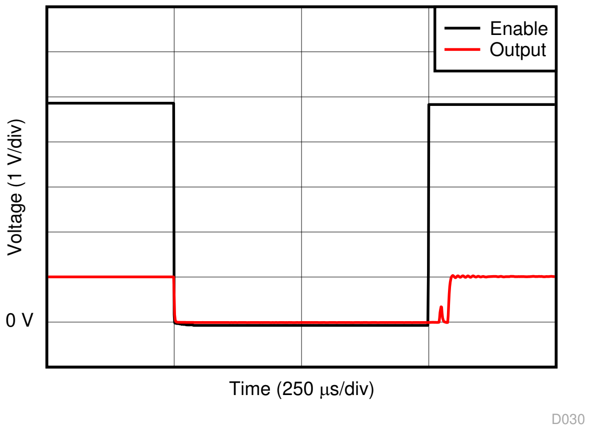


Figure 8-7. Output Disable and Enable Response

9 Power Supply Recommendations

The input circuitry of the INA190-EP accurately measures beyond the power-supply voltage, V_S. For example, V_S can be 5 V, whereas the bus supply voltage at IN+ and IN– can be as high as 40 V. However, the output voltage range of the OUT pin is limited by the voltage on the VS pin. The INA190-EP also withstands the full differential input signal range up to 40 V at the IN+ and IN– input pins, regardless of whether the device has power applied at the VS pin. There is no sequencing requirement for V_S and V_{IN+} or $V_{IN–}$.

10 Layout

10.1 Layout Guidelines

- Connect the input pins to the sensing resistor using a Kelvin or 4-wire connection. This connection technique makes sure that only the current-sensing resistor impedance is detected between the input pins. Poor routing of the current-sensing resistor commonly results in additional resistance present between the input pins. Given the very low ohmic value of the current resistor, any additional high-current carrying impedance can cause significant measurement errors.
- Place the power-supply bypass capacitor as close as possible to the device power 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.
- When routing the connections from the current-sense resistor to the device, keep the trace lengths as short as possible. The input filter capacitor C_F should be placed as close as possible to the input pins of the device.

10.2 Layout Examples

Figure 10-1. Recommended Layout for SC70 (DCK) Package

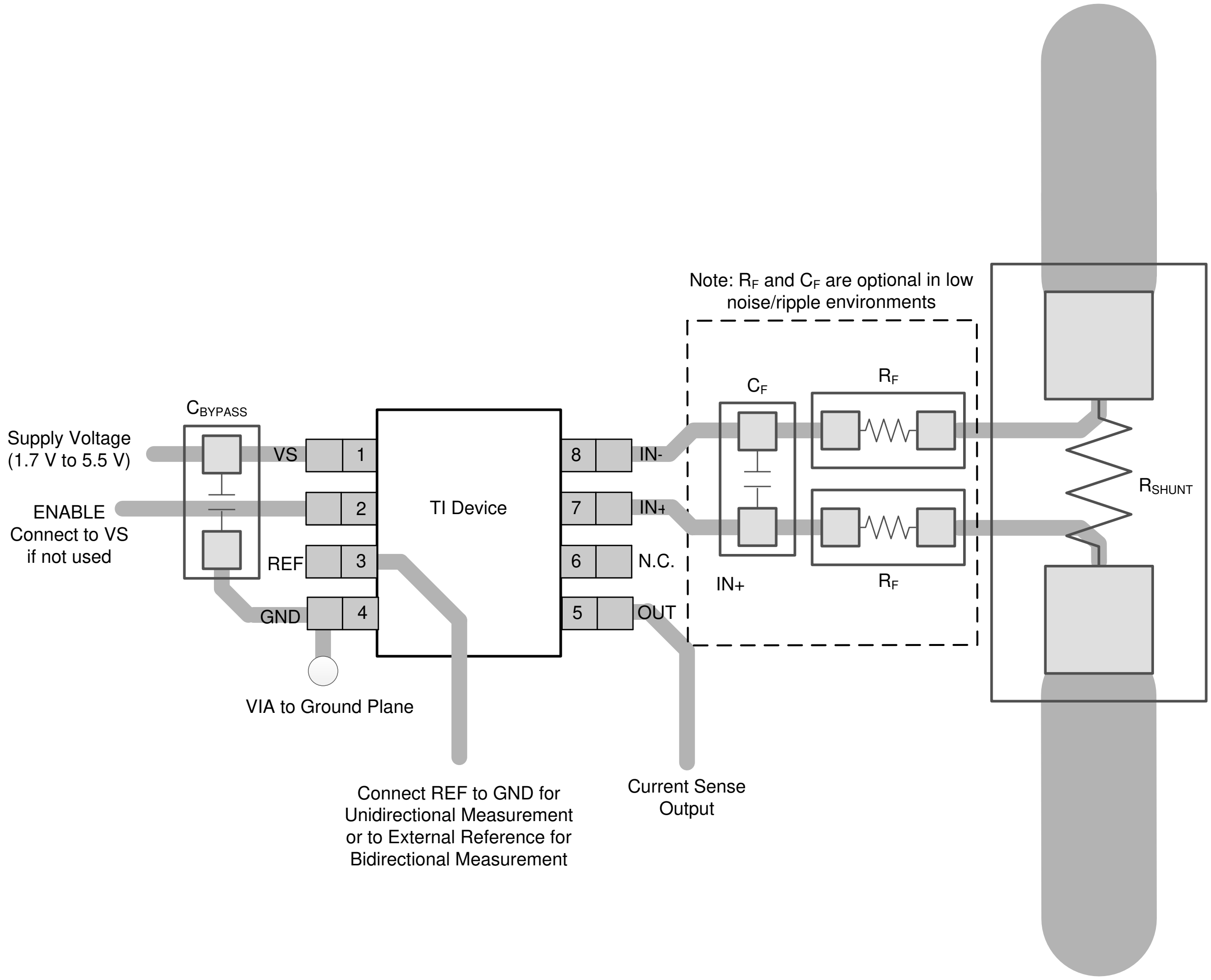


Figure 10-2. Recommended Layout for SOT23-8 (DDF) Package

11 Device and Documentation Support

11.1 Documentation Support

11.1.1 Related Documentation

For related documentation see the following:

- Texas Instruments, *INA190EVM* user's guide
- Texas Instruments, *Closed-Loop Analysis of Load-Induced Amplifier Stability Issues Using ZOUT* application report

11.2 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. Click on *Subscribe to updates* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

11.3 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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11.4 Trademarks

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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

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.

PACKAGE OPTION ADDENDUM

PACKAGING INFORMATION

Orderable part number	Status (1)	Material type (2)	Package | Pins	Package qty | Carrier	RoHS (3)	Lead finish/ Ball material (4)	MSL rating/ Peak reflow (5)	Op temp (°C)	Part marking (6)
INA190A1NDDFREP	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2LVF
INA190A1NDDFREP.A	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2LVF
INA190A2NDDFREP	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2LXF
INA190A2NDDFREP.A	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2LXF
INA190A3NDDFREP	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M1F
INA190A3NDDFREP.A	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M1F
INA190A4NDDFREP	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M3F
INA190A4NDDFREP.A	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M3F
INA190A5NDDFREP	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M5F
INA190A5NDDFREP.A	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M5F
V62/21612-01XE	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2LVF
V62/21612-02XE	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2LXF
V62/21612-03XE	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M1F
V62/21612-04XE	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M3F
V62/21612-05XE	Active	Production	SOT-23-THIN (DDF) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-55 to 150	2M5F

[1] **Status:** For more details on status, see our product life cycle.

[2] **Material type:** When designated, preproduction parts are prototypes/experimental devices, and are not yet approved or released for full production. Testing and final process, including without limitation quality assurance, reliability performance testing, and/or process qualification, may not yet be complete, and this item is subject to further changes or possible discontinuation. If available for ordering, purchases will be subject to an additional waiver at checkout, and are intended for early internal evaluation purposes only. These items are sold without warranties of any kind.

[3] **RoHS values:** Yes, No, RoHS Exempt. See the TI RoHS Statement for additional information and value definition.

[4] **Lead finish/Ball material:** Parts may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

[5] **MSL rating/Peak reflow:** The moisture sensitivity level ratings and peak solder (reflow) temperatures. In the event that a part has multiple moisture sensitivity ratings, only the lowest level per JEDEC standards is shown. Refer to the shipping label for the actual reflow temperature that will be used to mount the part to the printed circuit board.

[6] **Part marking:** There may be an additional marking, which relates to the logo, the lot trace code information, or the environmental category of the part.

Multiple part markings will be inside parentheses. Only one part marking contained in parentheses and separated by a "~" will appear on a part. If a line is indented then it is a continuation of the previous line and the two combined represent the entire part marking for that device.

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OTHER QUALIFIED VERSIONS OF INA190-EP :

- Catalog : INA190

- Automotive : INA190-Q1

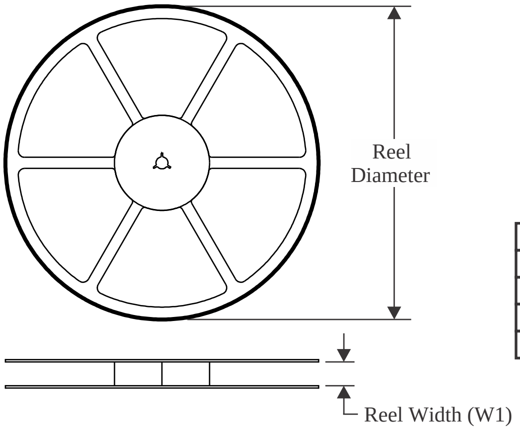
NOTE: Qualified Version Definitions:

- Catalog - TI's standard catalog product

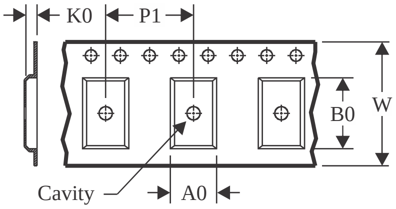
- Automotive - Q100 devices qualified for high-reliability automotive applications targeting zero defects

TAPE AND REEL INFORMATION

REEL DIMENSIONS

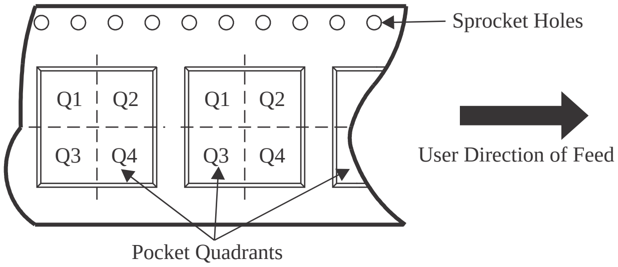


TAPE DIMENSIONS



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

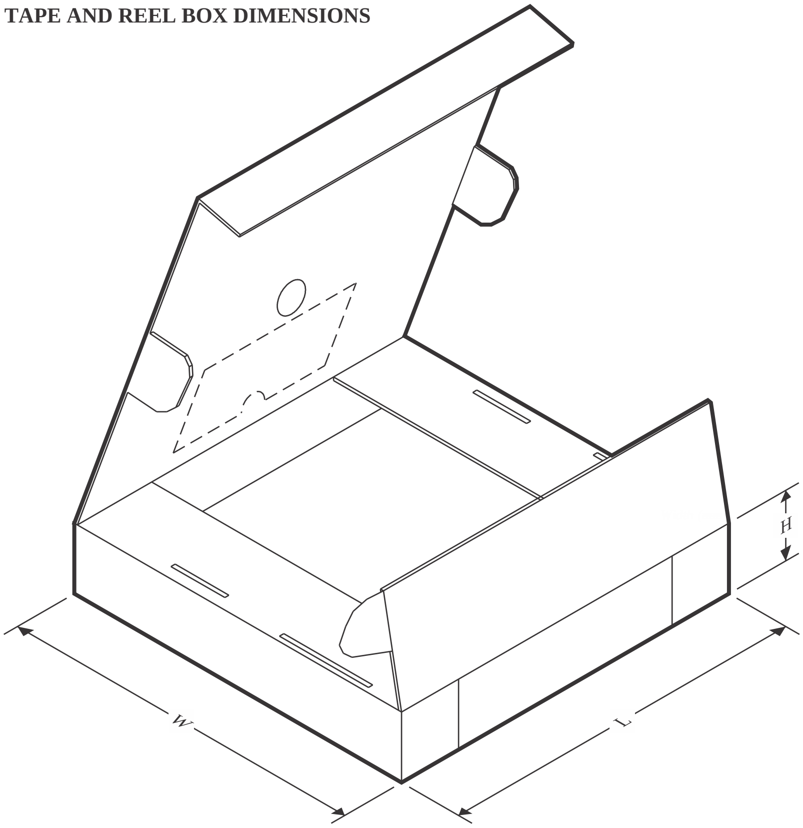
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

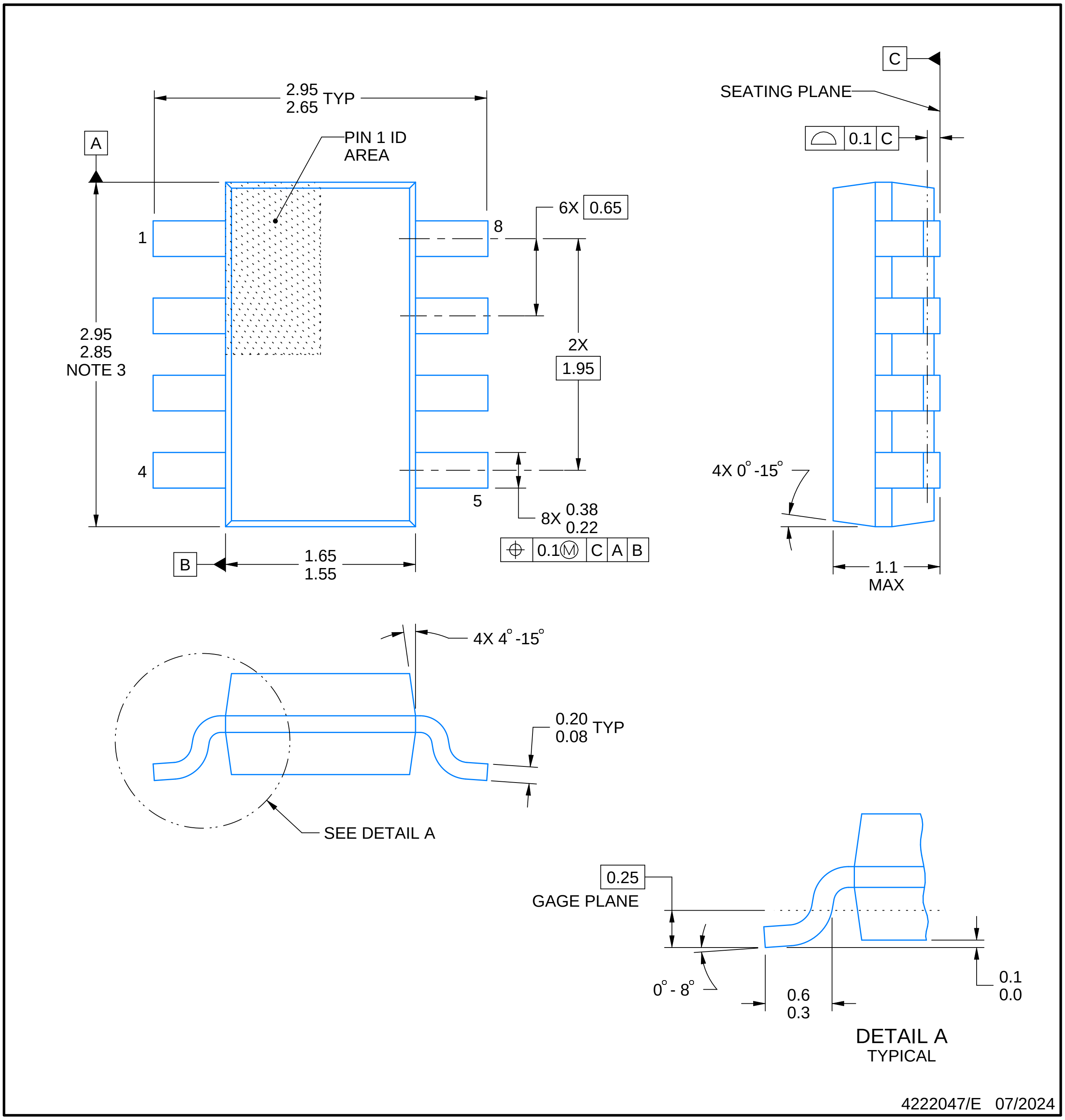
Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
INA190A1NDDFREP	SOT-23-THIN	DDF	8	3000	180.0	8.4	3.2	3.2	1.4	4.0	8.0	Q3
INA190A2NDDFREP	SOT-23-THIN	DDF	8	3000	180.0	8.4	3.2	3.2	1.4	4.0	8.0	Q3
INA190A3NDDFREP	SOT-23-THIN	DDF	8	3000	180.0	8.4	3.2	3.2	1.4	4.0	8.0	Q3
INA190A4NDDFREP	SOT-23-THIN	DDF	8	3000	180.0	8.4	3.2	3.2	1.4	4.0	8.0	Q3
INA190A5NDDFREP	SOT-23-THIN	DDF	8	3000	180.0	8.4	3.2	3.2	1.4	4.0	8.0	Q3

TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

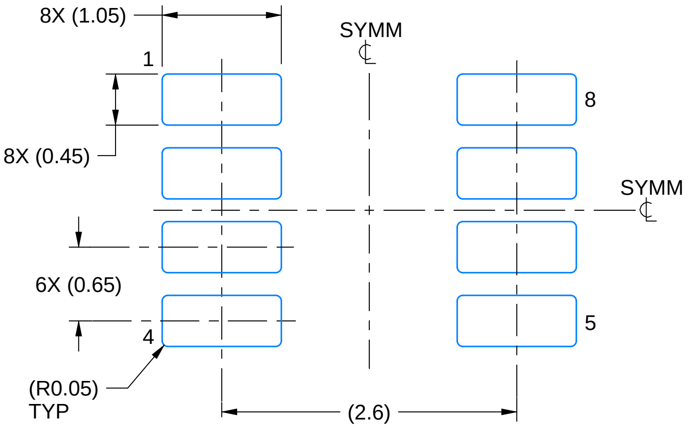
Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
INA190A1NDDFREP	SOT-23-THIN	DDF	8	3000	210.0	185.0	35.0
INA190A2NDDFREP	SOT-23-THIN	DDF	8	3000	210.0	185.0	35.0
INA190A3NDDFREP	SOT-23-THIN	DDF	8	3000	210.0	185.0	35.0
INA190A4NDDFREP	SOT-23-THIN	DDF	8	3000	210.0	185.0	35.0
INA190A5NDDFREP	SOT-23-THIN	DDF	8	3000	210.0	185.0	35.0



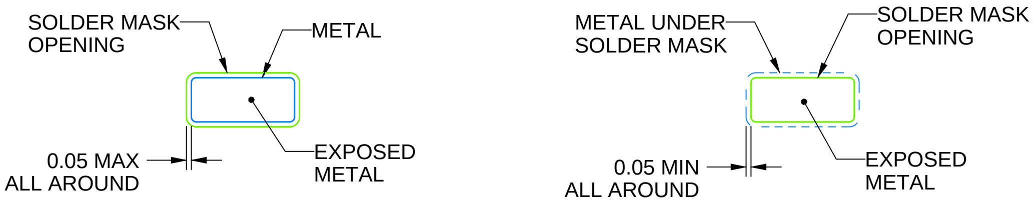
NOTES:

1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.

EXAMPLE BOARD LAYOUT



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:15X



NON SOLDER MASK
DEFINED

SOLDER MASK
DEFINED

SOLDER MASK DETAILS

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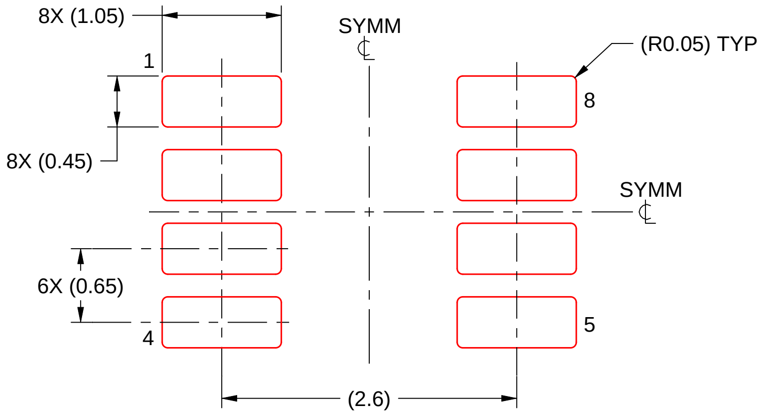
NOTES: (continued)

4. Publication IPC-7351 may have alternate designs.
5. Solder mask tolerances between and around signal pads can vary based on board fabrication site.



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE:15X

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NOTES: (continued)

6. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
7. Board assembly site may have different recommendations for stencil design.

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