Analog Engineer's Circuit

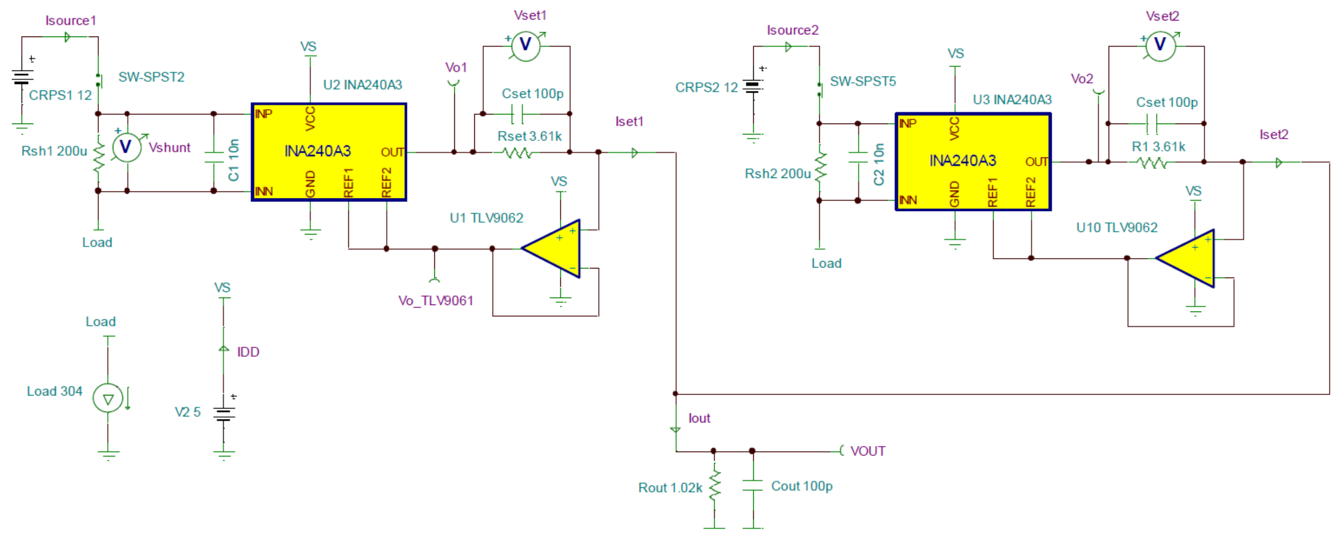
Circuit to measure multiple redundant source currents with singled-ended signal

Amplifiers

Input			Output			Error	Supply		
I_{LOAD} Min	$I_{LOAD\ Max}$	V_{CM}	$I_{OUT\ Min}$	$I_{OUT\ Max}$	Bandwidth	I_{LOAD} > 45 A	I_{DD}	V_S	V_{ee}
5A	304A	12V	42.1µA	1.6842mA	400kHz	2.1% maximum at full-scale range	N × (2.4mA + 750µA) + I_{OUT}	5V	GND (0V)

Design Description

This circuit demonstrates how to convert a voltage-output, current-sense amplifier (CSA) into a current-output circuit using the Howland Current Pump method and operational amplifier (op amp). Furthermore, this circuit demonstrates how to design two separate circuits to measure two separate, but redundant supplies powering one load.



Design Notes

1. The *Getting Started with Current Sense Amplifiers* video series introduces implementation, error sources, and advanced topics for using current sense amplifiers.
2. Choose precision 0.1% resistors to limit gain error at higher currents.
3. The output current (I_{OUT}) is sourced from the VS supply, which adds to the I_Q of the current sense amplifier.
4. Use the V_{OUT} versus I_{OUT} curve ("claw-curve") of the CSA (INA240A3) to set the I_{OUT} limit during maximum power. If a higher signal current is needed, then add an op amp buffer to the output of the current sense amplifier. A buffer on the output allows for smaller R_{OUT}.
5. For applications with higher bus voltages, simply substitute in a bidirectional current sense amplifier with a higher rated input voltage.
6. The V_{OUT} voltage is the input common-mode voltage (V_{CM}) for the op amp.
7. Offset errors can be calibrated out with one-point calibration given that a known sense current is applied and the circuit is operating in the linear region. Gain error calibration requires a two-point calibration.
8. Include a small feed-forward capacitor (C_{SET}) to increase BW and decrease V_{OUT} settling time to a step response in current. Increasing C_{SET} too much introduces gain peaking in the system gain curve, which results in output overshoot to a step response.
9. Follow best practices for printed-circuit board (PCB) layout according to the data sheet: place the decoupling capacitor close to the VS pin, routing the input traces for IN+ and IN– as a differential pair, and so forth.

Design Steps

1. Choose an available current-sense amplifier (CSA) that meets the common-mode voltage requirement. For this design the INA240A3 is selected.
   - Note that choosing the most optimal CSA for the system requires balancing tradeoffs in CSA offset, CSA gain error, shunt resistor power rating and thus total circuit design could require multiple iterations to achieve the satisfactory error over the entire dynamic range of the load.
2. Determine the maximum output current ($I_{SET\_100\%}$) and maximum output swing ($V_{O\_ISYS\_MAX}$) of the INA240A3. Use the output current vs output voltage curve in the data sheet. For this design, choose the maximum I_{SET} to be 850 µA with a maximum output swing of {Vs – 0.2V} = 4.8V = $V_{O\_ISYS\_MAX}$.
3. Given the ADC full-scale range (V_{ADC_FSR} = 1.8V), the number of sources to measure (N = 2), and the maximum CSA output current when the source is at 100% power ($I_{SET\_100\%}$ = 850µA), calculate the maximum allowable R_{OUT} which converts signal current to signal voltage for ADC. For this design R_{OUT} = 1020 Ω is selected.

$$I_{OUT\_I_{SYS\_MAX}} = \text{Total signal current from all N channels when system/load current is at its maximum (304-A).}$$

$$I_{SET1\_100\%} = \text{Signal current from INA240A3 channel 1 when Source 1 is at 100\% power (152-A).}$$

$$V_{ADC\_FSR} = V_{OUT\_I_{SYS\_MAX}} < 1.8V$$

$$I_{OUT\_I_{SYS\_MAX}} = I_{SET1\_100\%} + I_{SET2\_100\%} = I_{SET\_100\%} \times N$$

$$V_{OUT\_I_{SYS\_MAX}} = I_{OUT\_I_{SYS\_MAX}} \times R_{OUT}$$

$$\therefore R_{OUT} < \frac{V_{OUT\_I_{SYS\_MAX}}}{I_{OUT\_I_{SYS\_MAX}}} = \frac{1.8V}{850\mu A \times 2} = 1058.82\Omega$$

$$\rightarrow R_{OUT} = 1020\Omega, 0.1\%$$

$$\rightarrow V_{OUT\_I_{SYS\_MAX}} = 1.734V < 1.8V$$

4. Using the following system of equations, we can solve for the minimum allowable R_{SET}. For this design, R_{SET} = 3610 Ω is selected.

$$V_{OUT\_I_{SYS\_MAX}} = I_{OUT\_I_{SYS\_MAX}} \times R_{OUT}$$

$$V_{OUT\_I_{SYS\_MAX}} = V_{O\_I_{SYS\_MAX}} - V_{SET\_100\%}$$

$$V_{SET\_100\%} = I_{SET\_100\%} \times R_{SET}$$

$$\therefore R_{SET} \geq \frac{V_{O\_I_{SYS\_MAX}} - I_{SET\_100\%} \times R_{OUT} \times N}{I_{SET\_100\%}}$$

$$\therefore R_{SET} \geq \frac{V_{O\_I_{SYS\_MAX}}}{I_{SET\_100\%}} - \left(R_{OUT} \times N\right) = 3607.06\Omega$$

$$\rightarrow R_{SET} = 3610\Omega, 0.1\%$$

5. Using the following system of equations, solve for the maximum allowable shunt resistor. For this design, choose R_{SHUNT} = 200 µΩ.

$$V_{SET1\_100\%} = R_{SET} \times I_{SET1\_100\%} = 3610\Omega \times 850\mu A = 3.0685V$$

$$V_{SHUNT\_100\%} = \frac{V_{SET1\_100\%}}{Gain_{INA240A3}} = \frac{3.0685V}{100 V/V} = 30.685mV$$

$$R_{SHUNT} \leq \frac{V_{SHUNT\_100\%}}{I_{SOURCE\_100\%}} = \frac{30.685mV}{152A}$$

$$\therefore R_{SHUNT} \leq 201.88\mu\Omega$$

$$\rightarrow R_{SHUNT} = 200\mu\Omega, 1\%$$

6. Check that the common-mode voltage (V_{CM}) and output voltage ($V_{O\_TLV9061}$) of the TLV9061 are in the operational region when the circuit is sensing the minimum required 5% source current. The TLV9061 device is a rail-to-rail-input-output (RRIO) op amp so it can operate with very small V_{CM} and output voltages, but A_{OL} will vary. Testing conditions from the data sheet for CMRR and A_{OL} show that choosing $V_{OUT\_5\%}$ ≥ 40mV provides sufficient A_{OL} when circuit sensing minimum load current.
   - If a lower operational V_{CM} is needed, then consider providing a small negative voltage source to the negative supply pin to extend the range of the op amp or current-sense amplifier.

$$V_{O\_MIN\_TLV9061} = 40mV$$

$$V_{SHUNT\_5\%} = 5\% \times I_{SOURCE\_MAX} \times R_{SHUNT} = 7.6A \times 200\mu\Omega$$

$$\therefore V_{SHUNT\_5\%} = 1.52mV$$

$$V_{OUT\_5\%} = V_{SHUNT\_5\%} \times Gain \times \frac{R_{OUT}}{R_{SET}}$$

$$\therefore V_{OUT\_5\%} = 42.94mV > V_{O\_MIN\_TLV9061}$$

7. Using the following equations, calculate and tabulate the total, worst-case RSS error over the dynamic range of the source.

$$RE_{MAX\_P} = \text{Max Positive Relative Error} = \frac{V_{OUT\_MAX} - V_{OUT\_TYP}}{V_{OUT\_TYP}}$$

$$RE_{MAX\_N} = \text{Max Negative Relative Error} = \frac{V_{OUT\_MIN} - V_{OUT\_TYP}}{V_{OUT\_TYP}}$$

$$E_{RSS} = \sqrt{{e_{V_{OS\_CSA}}}^2 + {e_{V_{OS\_OPA}}}^2 + {e_{R_{SHUNT}}}^2 + {e_{Gain\_CSA}}^2 + {e_{R_{OUT}}}^2 + {e_{R_{SET}}}^2}$$

$$V_{OUT\_TYP} = I_{SOURCE1} \times R_{SHUNT\_TYP} \times G_{TYP} \times \frac{R_{OUT\_TYP}}{R_{SET\_TYP}}$$

$$V_{OUT\_MAX} = \left[\left(I_{SOURCE1} \times R_{SHUNT\_MAX} + V_{OS\_CSA\_MAX}\right) \times G_{MAX\_CSA} + V_{OS\_OPA\_MAX}\right] \times \frac{R_{OUT\_MAX}}{R_{SET\_MIN}}$$

$$V_{OUT\_MIN} = \left[\left(I_{SOURCE1} \times R_{SHUNT\_MIN} - V_{OS\_CSA\_MAX}\right) \times G_{MIN\_CSA} - V_{OS\_OPA\_MAX}\right] \times \frac{R_{OUT\_MIN}}{R_{SET\_MAX}}$$

$$T_{MAX} = 80^{o}C$$

$$\Delta T_{MAX} = 80^{o}C - 25°C = 55°C$$

$$R_{SHUNT} = 200\mu\Omega,\ 0.1\%,\ 175\frac{ppm}{°C}$$

$$V_{VS} = 5V; V_{CM} = 12V$$

$$V_{OSI\_OPA} = \pm 2mV$$

$$V_{OS\_OPA\_CMRR} = \left|V_{OUT} - 2.5V\right| \times 10^{(-80dB/20dB)}$$

$$V_{OS\_OPA\_MAX} = V_{OSI\_OPA} + V_{OS\_OPA\_CMRR} + \Delta T_{MAX} \times \left(530\frac{nV}{°C}\right)$$

$$V_{OSI\_CSA\_MAX} = \pm 25\mu V$$

$$V_{OS\_CSA\_CMRR\_MAX} = \left|12V - V_{CM}\right| \times 10^{\left(-CMRR_{MIN}/20dB\right)} = 0$$

$$V_{OS\_CSA\_PSRR\_MAX} = \left|5V - V_{VS}\right| \times PSRR_{MAX} = 0$$

$$V_{OS\_Drift\_MAX} = \Delta T_{MAX} \times \left(\frac{\Delta V_{OS}}{\Delta T}\right) = 55°C \times \left(250\frac{nV}{°C}\right) = \pm 13.75\mu V$$

$$V_{OS\_CSA\_MAX} = V_{OSI\_MAX} + V_{OS\_CMRR} + V_{OS\_PSRR} + V_{OS\_Drift}$$

$$V_{OS\_CSA\_MAX} = \pm 38.75\mu V$$

$$e_{V_{OS\_CSA}} = {V_{OS\_CSA\_MAX}}/{V_{SHUNT\_IDEAL}} \times 100$$

$$e_{V_{OS\_OPA}} = {V_{OS\_OPA\_MAX}}/{V_{SET\_IDEAL}} \times 100$$

$$e_R = e_{R_{TOLERANCE}} + e_{R_{DRIFT}}$$

$$e_{R_{SHUNT}} = 1\% + \Delta T_{MAX} \times TC = 1\% + 55°C \times \left(175\frac{ppm}{°C}\right) \times 10^{-4} = 1.963\%$$

$$e_{R_{SET}} = e_{R_{OUT}} = 1\% + 55°C \times \left(50\frac{ppm}{°C}\right) \times 10^{-4} = 1.275\%$$

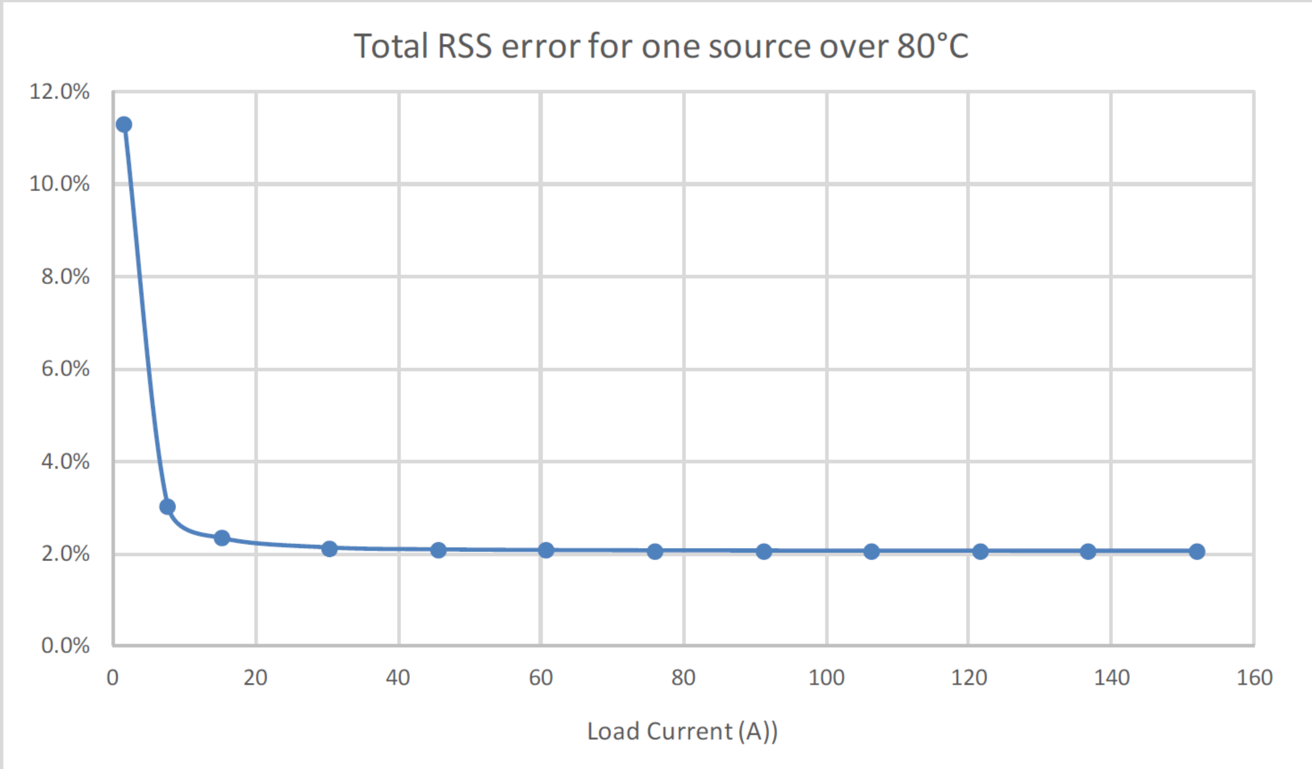
$$e_{GAIN\_CSA\_25C} = \pm 0.2\%$$

$$e_{GAIN\_Drift\_CSA\_MAX} = \Delta T_{MAX} \times \left(2.5\frac{ppm}{°C}\right) \times 10^{-4} = \pm 0.01375\%$$

$$G_{MAX} = G_{TYP} \times \left(1 + e_{25C\_MAX} + e_{Drift\_MAX}\right) = 100\ \frac{V}{V} \times (1.002138) = 100.2138\ \frac{V}{V}$$

$$G_{MIN} = G_{TYP} \times \left(1 - e_{25C\_MAX} - e_{Drift\_MAX}\right) = 100\ \frac{V}{V} \times \left(0.997862\right) = 99.7862\ \frac{V}{V}$$

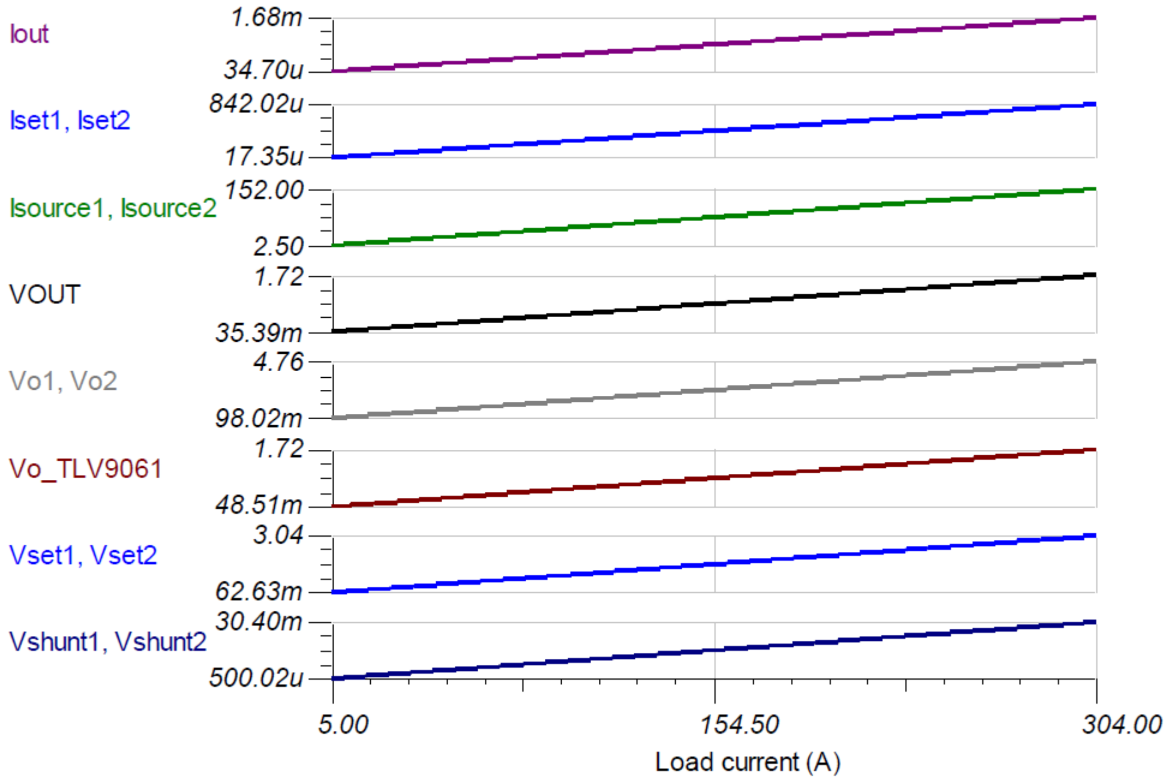
8. Plot the total error as a function of load current



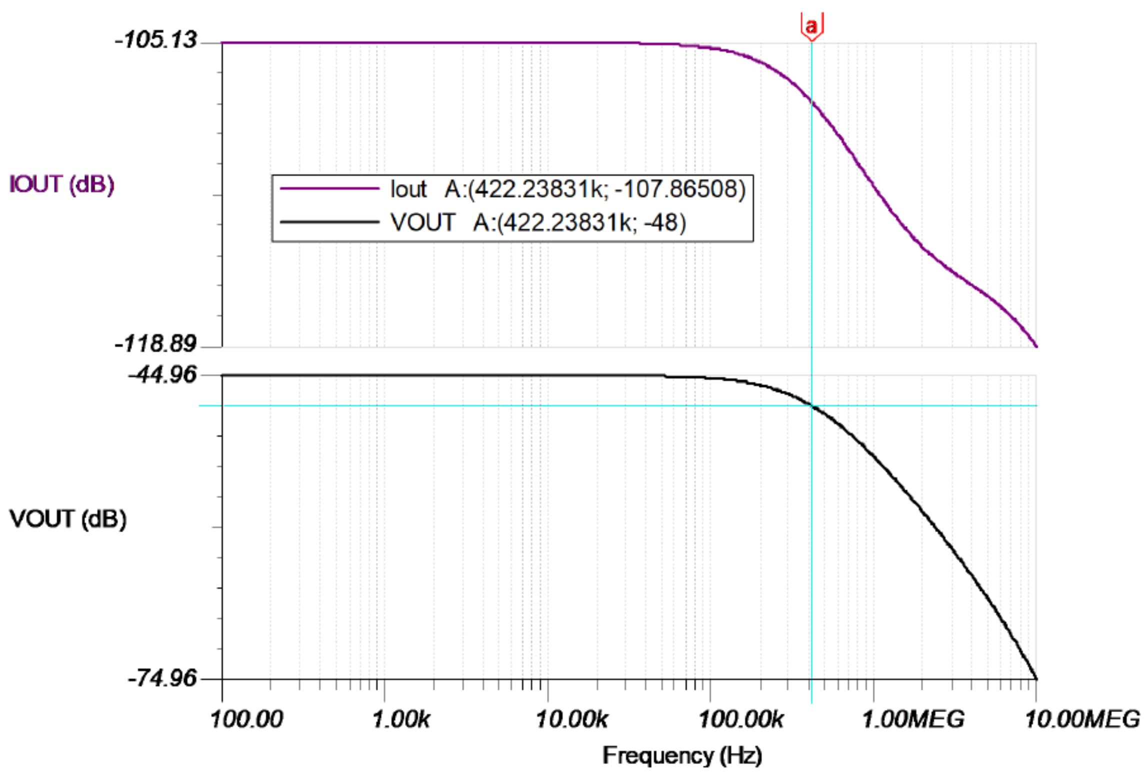
Design Simulations

DC Simulation Results

The following graph shows a linear output response for load currents from 5A to 304A.



AC Simulation Result – I_{LOAD} to I_{OUT} (V_{OUT}) circuit gain



Design References

See *Analog Engineer's Circuit Cookbooks* for TI's comprehensive circuit library.

Getting Started with Current Sense Amplifiers video series

https://training.ti.com/getting-started-current-sense-amplifiers

Current Sense Amplifiers on TI.com

http://www.ti.com/amplifier-circuit/current-sense/products.html

Comprehensive Study of the Howland Current Pump

http://www.ti.com/analog/docs/litabsmultiplefilelist.tsp?literatureNumber=snoa474a&docCategoryId=1&familyId=78

For direct support from TI Engineers use the E2E community

http://e2e.ti.com

Design Featured Current Sense Amplifier

INA240A3	
V_S	2.7V to 5.5V (operational)
V_{CM}	–4V to 80V
Swing to V_S (V_{SP})	V_S – 0.2V
V_{OS}	±25μV at 12V V_{CM}
I_{Q_MAX}	2.4mV
I_{IB}	90μA at 12V
BW	400kHz
# of channels	1
Body size (including pins)	4mm × 3.91mm
www.ti.com/product/ina240	

Design Featured Operational Amplifier

TLV9061 (TLV9061S is shutdown version)	
V_S	1.8V to 5.5V
V_{CM}	(V–) – 0.1V < V_{CM} < (V+) + 0.1V
CMRR	103dB
A_{OL}	130dB
V_{OS}	±1.6mV maximum
I_Q	750μA maximum
I_B (input bias current)	± 0.5pA
GBP (gain bandwidth product)	10MHz
# of channels	1 (2 and 4 channel packages available)
Body size (including pins)	0.80mm × 0.80mm
www.ti.com/product/tlv9061	

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265