High-side current sources for industrial applications

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Introduction

The use of current sources in industrial applications is widespread because the current-based signal provides higher noise immunity than voltage-based signals in a harsh industrial environment. Current is used to carry information signals in 4–20-mA loops and also for excitation of passive sensors like resistors. High-side current sources are generally trickier to design compared to low-side current sinks. This article introduces and compares different topologies used to implement a high-side current source for industrial applications, and includes evaluation of performance metrics for each topology.

Current source parameters and characterization

Table 1 shows current-source performance metrics, their definitions, and measurement units. Although it is possible to eliminate initial inaccuracies through calibration, it is not possible to compensate for temperature drifts and load regulation; thus, those drifts will determine the overall accuracy of the current source. If the current source is powering a sensor, the power supply rejection ratio (PSRR) and output impedance will determine the maximum bandwidth at which the current source is working. This is because the PSRR and output impedance deteriorate with increasing frequency and add error components to the measured signal.

In addition to static performance, dynamic performance must also be considered to ensure the stability of the current source against perturbation, especially if the current source will switch during operation or the load voltage will experience a step transient. The dynamic performance can be checked by testing the settling time upon step inputs.

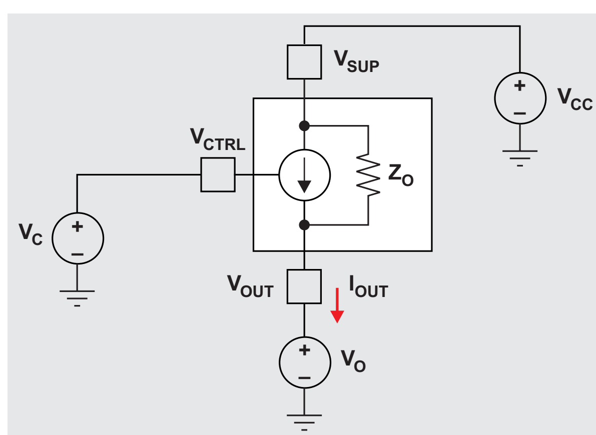
Although some of the parameters in Table 1 can only be predicted through calculations of component parametrics, it is also possible to verify many of them through simulation if component models are available. Simulation is a pretty easy step for verifying a specification within a given set of conditions.

Figure 1 shows a conceptual current source with supply-voltage, output-voltage and control-voltage sources. The majority of current source parameters can be

Table 1. Current-source performance specifications

	Parameter	Definition	Unit
Applicability	Output current range (I_{OUT})	Minimum and maximum possible output current	mA
Applicability	Compliance range	Minimum and maximum output voltage at which current is valid	V
Applicability	Maximum supply	Maximum acceptable supply	V
Initial accuracy		Inaccuracy before carrying any calibration	%
Accuracy	Temperature drift	Error due to temperature change (range >100°C)	ppm/°C
Accuracy	Load regulation	Change in output current vs. change in output voltage	%/V
Accuracy	Output noise	Total output noise over certain bandwidth	nA
Bandwidth	PSRR	Power supply rejection ratio	dB
Bandwidth	Output impedance (Z_O)	AC output impedance seen from the output node	Ω
Power efficiency		Output current divided by total current consumed by source	%
Dynamic	Settling time: • Load step • Control step • Supply ramp	Settling time (of the output current) and stability upon a step in the load voltage or a step of the control input (configurable)	ns

Figure 1. Conceptual current source with different voltage sources



verified by conducting various sweeps of those supplies, which are summarized in Table 2.

Table 2. Current-source performance simulation or prediction

Parameter	Simulation?	Prediction/Verification (Conditions)
Output current range	Yes	Typically calculated from component parameters, but can be simulated later For programmable sources: DC transfer function; V_C swept from 0 to V_{C_max}
Compliance range and load regulation	Yes	DC transfer function analysis: V_O swept from 0 to V_{CC} (fixed V_{CC} and V_C) I_{OUT} change is regulation; limits of V_O at which I_{OUT} exceeds variation is compliance
Maximum supply	No	Typically not modeled; calculated from the maximum supply limit in the data sheet
Initial accuracy	No	Requires accurate models and statistical analysis; generally more convenient to calculate
Temperature drift	No	Not commonly supported with models; requires calculation
Output noise	Yes	Noise analysis: One AC source out of the three supplies (proper DC value for V_{CC}, V_C, V_O) I_{OUT} total noise at specific relevant frequency (f_C) represents system bandwidth
PSRR	Yes	AC transfer function analysis: AC source at V_{CC}; I_{OUT} (AC signal) in decibels is PSRR
Output impedance	Yes	AC transfer function analysis: AC source at V_O; $1/I_{OUT}$ (AC) linear is Z_O vs. frequency
Power efficiency	Yes	DC operating point analysis: I_{OUT}/I_{CC} (for specific V_{CC}, V_O and V_C)
Settling time • Load step • Control step • Supply ramp	Yes	Transient analysis: • Supply ramp: V_{CC} ramped from zero; I_{OUT} settling time and behavior is monitored • V_C step: V_C unit step (minimum to maximum); I_{OUT} settling to final value • V_O step: V_O unit step over compliance range limits; I_{OUT} settling to final value

The next step is to examine some topologies for current sources. To establish a basis for useful comparison, the application is limited to a high-side current source that can work off a 24-V industrial supply, assume a 10-mA output and 10-kHz bandwidth for noise, calculate the output impedance at DC and 1 kHz, and assume a midsupply (12 V) as the default output voltage.

Constant-current sources

Many applications require a constant-current source that is stable over supply drift, temperature drift, and output variations. The basic principle is to use an accurate voltage reference applied over a precision resistor to create an accurate current.

A shunt regulator and a MOSFET

Precision shunt regulators are among the most popular options for obtaining a voltage reference (V_{REF}). Providing the shunt regulator with a minimum current (I_Q) will ensure that the V_{REF} is applied on the set resistor (R_{SET}) as shown in Figure 2, where the circuit implementation uses the TLV431BQ regulator. The parameters calculation and simulation results are presented in Table 3.

The output current is calculated as $I_{OUT} = V_{REF}/R_{SET}$. This circuit provides a cost-effective solution with a reasonable error that is 1.2% (0.8% + 0.4%) over the temperature range, and a moderate initial accuracy of 0.7% that can be compensated with resistor trimming. This circuit is suitable for applications with 7- to 8-bit resolution. The 100-Ω resistors and 100-nF capacitor around U1 are necessary for circuit stability. This circuit can work with a high supply voltage with only some limited dynamic performance.

Figure 2. Current source using a shunt regulator

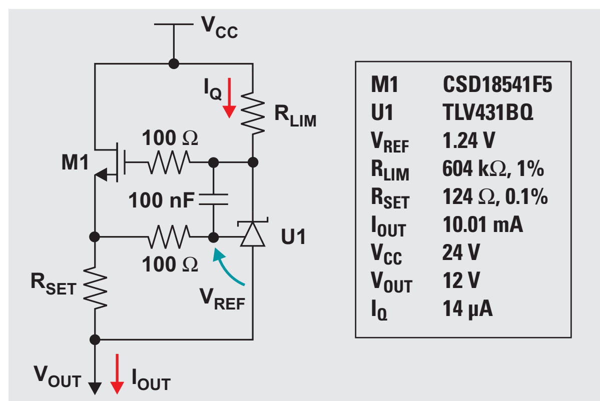


Table 3. Current-source specifications using a shunt regulator

Parameter	Calculation and/or Simulation Results
Output current range	Set by M1 max I_{DS}, and M1 max power; $I_{OUT\_max} = P_{max\_M1}/V_{dsmax\_M1} = 0.5/23 = 21$ mA At lower I_{OUT}, the initial error due to I_Q becomes significant
Compliance range	$V_{OUT\_max} = V_{CC} - (V_{REF} + V_{GSTH\_M1} + I_Q \times R_{LIM}) = 24 - (1.24 + 1.75 + 1.8) \approx 20$ V
Maximum supply	$V_{max\_M1} = 60$ V, then $I_{OUT\_max} = 8$ mA
Initial accuracy	$(1 + \Delta V_{REF})/(1 - \Delta R_{SET}) + I_Q/I_{OUT} = (1 + 0.005)/0.999 + 0.001 = 0.7\%$
Temperature drift	$\Delta V_{REF}/V_{REF} = 11$ mV/1.24 V = 0.8% over temperature range
Load regulation	0.4% over compliance range, or 2 µA/V
Output noise	5.2 nA over 10 kHz
PSRR	–75 dB at 10 kHz
Output impedance	588 kΩ at DC, 46.5 kΩ at 1 kHz
Power efficiency	100%
Settling time	Supply ramp: 114 µs (with large overshoot) Load step (9 V): 700 µs (with large undershoot)

Shunt regulator and op amp

It is possible to eliminate some of the drawbacks of the circuit shown in Figure 2. Figure 3 shows a current source that uses a shunt regulator and an operational amplifier (op amp) to buffer the voltage reference. In this circuit, $I_{OUT} = V_{REF}/R_{SET}$ and the 80-kΩ resistor ensures that the shunt regulator gets the minimum required current to turn on. This circuit can achieve a wide compliance range, very-high PSRR and Z_O, and excellent load regulation. The op-amp offset drift and reference drift contribute directly to the overall accuracy. This topology can achieve very high accuracy when using precision components. Table 4 lists the performance metrics.

Figure 3. Current source using a shunt regulator and op amp

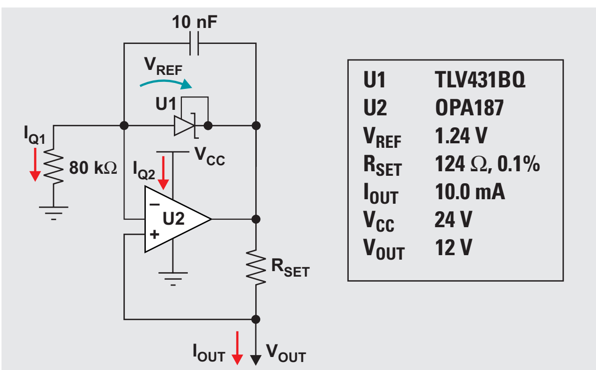


Table 4. Current-source specifications using a shunt regulator and op amp

Parameter	Calculation and/or Simulation Results
Output current range	Set by U2 max I_{OUT} and U2 max power; $I_{OUT\_max} < 30$ mA At lower I_{OUT}, the relative error becomes significant
Compliance range	$V_{OUT\_max} = V_{CC} - V_{REF} - V_{OUT\_max\_U2} = 24 - 1.24 - 0.5 \approx 22.25$ V Simulation results 21.25 V $V_{OUT\_min} \approx 0.25$ V (I_Q goes below limit for U1 to function)
Maximum supply	$V_{max\_U2} = 36$ V
Initial accuracy	$(1 + \Delta V_{REF} + V_{OS\_U2})/(1 - \Delta R_{SET}) = (1 + 0.005 + 0.00001)/0.999 = 1\%$
Temperature drift	$\Delta V_{REF} + \Delta V_{OS\_U2}/V_{REF} = (11\text{ mV} + 5\text{ µV})/1.24\text{ V} = 0.9\%$ over temperature range
Load regulation	0% over compliance range
Output noise	16.4 nA over 10 kHz
PSRR	–95 dB at 10 kHz
Output impedance	6.5 MΩ at DC, 76 kΩ at 1 kHz
Power efficiency	$I_{OUT}/I_{CC} = I_{OUT}/(I_{OUT} + I_{Q1} + I_{Q2}) = 10/10.25 = 97\%$
Settling time	Supply ramp: 800 µs (with some overshoot) Load step (12 V): 250 µs (with undershoot)

Programmable current sources

To complete the current-source evaluation, there are two topologies for implementing a programmable high-side current source with the control voltage referenced to ground. They are the modified Howland circuit and cascaded op amps.

Modified Howland circuit

As shown in Figure 4, a Howland circuit has been modified to have a buffer in the feedback loop. The output current of this circuit is calculated with Equation 1.

$$I_{OUT} = \frac{A_V}{R_{SET}} V_C \tag{1}$$

where the A_V gain is equal to R2/R1.

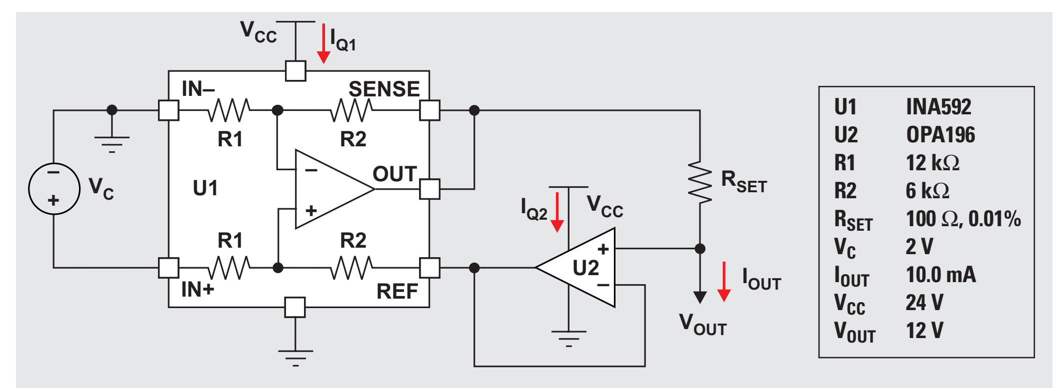
For the device chosen (the INA592), the gain equals 0.5, resulting in a 5-mA/V conversion gain. This circuit is quite interesting, as it is capable of driving bipolar (sink or source) current. The output impedance is proportional to the mismatch of R1s and R2s; implementing the circuit with a precision difference amplifier ensures the best matching for resistors.

The circuit performance is sensitive to source resistance, as the input impedance equals R1||R2 = 4 kΩ in the given circuit. As shown in Tabel 5, this circuit offers very good accuracy with a wide compliance range and excellent dynamic performance. The trade-off is a slight increase in noise and lower efficiency.

Table 5. Modified Howland current source specifications

Parameter	Calculation and/or Simulation Results
Output current range	Set by U1 max I_{OUT} and max power, $I_{OUT\_max} < 60$ mA At lower I_{OUT}, the relative error increases
Compliance range	V_{OUT_max} is set by V_{IN_U2} and $V_{OUT\_max\_U1}$ Simulation : 22.4-V V_{OUT_min} is determined by U1 minimum input (practical value = 0.2 V)
Maximum supply	V_{max_U1} = 36 V
Initial accuracy (excluding V_C)	$[1 + V_{OS\_U1}/V_C + 2 \times V_{OS\_U2}/V_C]/(1 - \Delta R_{SET}) = (1 + 0.00002 + 0.00005)/0.9999 \approx 0.02\%$
Temperature drift	$\Delta V_{OS\_U1}/V_C + 2 \times \Delta V_{OS\_U2}/V_C = 40\ \mu + 250\ \mu = 0.03\%$ over temperature
Load regulation	0.1% over compliance range
Output noise	17.8 nA over 10 kHz
PSRR	–60 dB at 10 kHz
Output impedance	3 MΩ at DC, 109 kΩ at 1 kHz
Power efficiency	$I_{OUT}/I_{CC} = I_{OUT}/(I_{OUT} + I_{Q1} + I_{Q2})$ = 10/12.4 = 80%
Settling time	Supply ramp: 6.8 µs (no overshoot) Load step (12 V): Large undershoot during transition Output current step (10 mA): Instant settling

Figure 4. Modified Howland current source using a difference amplifier



Cascaded op amps

The topology shown in Figure 5 uses a buffer to copy the control voltage (V_C) over to V1, applied on R1 and resulting in I1 current. Then, another buffer copies the V2 voltage to V3 over R3, which establishes the output current level. The output current is calculated with Equation 2.

$$I_{OUT} = \frac{R2}{R1}\frac{V_C}{R3} \quad (2)$$

which results in a 5-mA/V conversion gain. I1 is set to be $0.2 \times I_{OUT}$.

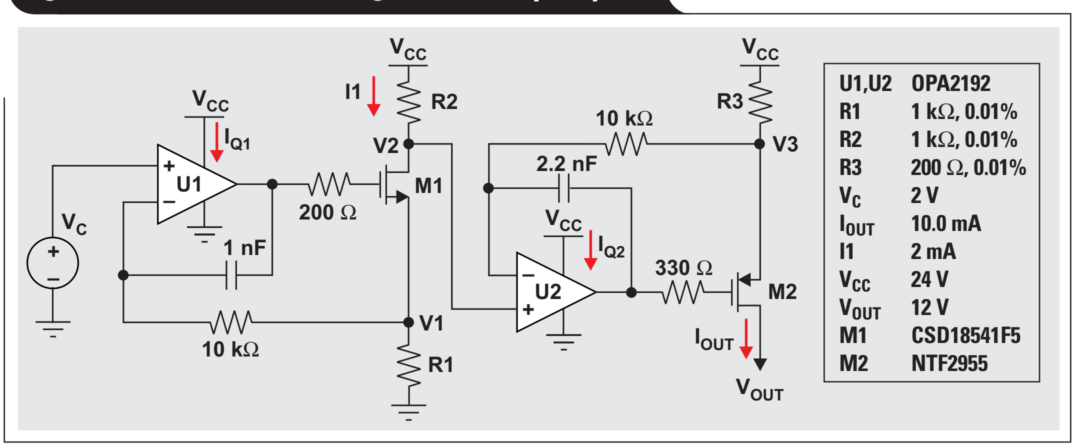
A lower I1 current means lower power but higher noise. Error analysis shows that equal offsets of U1 and U2 will eliminate the op-amp offset error. Using the dual op-amp package ensures offset tracking between the two op amps. Feedback capacitors and output resistors (200 ohms for U1 and 300 ohms for U2) are necessary to maintain circuit stability.

The trade-off here is between current range and compliance range. For a 1:20 current range, voltage V3 will vary with the same ratio, so to maintain a few volts over R3 requires that U2 accept a close-to-supply input at a low current. This circuit offers a wide current range, a wide compliance range, excellent accuracy, low noise, and very high output impedance, along with great dynamic performance as shown in Table 6.

Table 6. Current-source specifications using cascaded op amps

Parameter	Calculation and/or Simulation Results
Output current range	Set by M2 max power, $I_{OUT\_max} = P_{max\_M2}/V_{DS\_max\_M2} = 2.3/22 \approx 100$ mA Note that higher current requires lower R1,R2 Lower I_{OUT} is set by $U2_{IN\_max}$ (for this case, 0 mA) Higher current reduces compliance range
Compliance range	V_{OUT_max} is set by $U2_{IN}$ max rather than $U1_{OUT}$ max, $V_{CC} - V_{IN\_max\_U2} = 22$ V_{OUT_min} is determined by U2 minimum input, practically value = 0.0 V
Maximum supply	$V_{max\_U1} = 36$ V
Initial accuracy (excluding V_C)	$(1 + \Delta R2)/(1 - \Delta R1)/(1 - \Delta R3) = 0.03\%$ for 0.01% resistors, or 0.3% for 0.1% resistors
Temperature drift	By tracking offsets, there is only resistor drift variation
Load regulation	0% over compliance range
Output noise	9.7 nA over 10 kHz
PSRR	–77 dB at 10 kHz
Output impedance	142 MΩ at DC, 1.35 MΩ at 1 kHz
Power efficiency	$I_{OUT}/I_{CC} = I_{OUT}/(I_{OUT} + I1 + I_{Q1} + I_{Q2}) = 10/14 = 71\%$
Settling time	Supply ramp: 180 µs (with no overshoot) Load step (12 V): no settling observed Output current step (10 mA): 140 µs with no overshoot (depends on feedback RC)

Figure 5. Current source using cascaded op amps



It is worth noting that there are many other topologies for current sources that vary in performance and applications, including floating voltage regulators, current drivers like TI's XTR300, current-output digital-to-analog converters like the DAC7760, and of course, current references like the REF200.

Conclusion

There are different performance metrics for industrial current sources and the various topologies require different evaluation and calculation methods. This article compared the performance of four different topologies used to implement industrial current sources.

References

1. Linden T. Harrison, "Current Sources and Voltage References," Newnes, 2005.
2. Collin Wells and David F. Chan, "High-Side Voltage-to-Current (V-I) Converter," Texas Instruments Precision Designs: Verified Design (SLAU502), June 2013.

Related Web sites

Product information:
OPA187, INA592, OPA196, OPA2192, XTR300 DAC7760, REF200

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