

A High-Voltage Bidirectional Current Source

by John Caldwell, Analog Applications Engineer, Texas Instruments

Integrated circuit (IC) difference amplifiers are a popular approach to building bidirectional current sources using the Howland current pump topology. Many engineers often are surprised to find that these circuits are limited, not by their output current, but by the output voltage they can produce across the load. Because the vast majority of IC difference amplifiers are designed to operate on 36 V power supplies, these circuits only produce the expected output current into low impedances. By combining an IC difference amplifier featuring an extremely wide input common-mode range with a bootstrapped power supply scheme, a modified Howland current pump topology is presented that allows for very wide power supply voltages. These elevated power supply voltages enable linear circuit operation over a broader range of load impedances. To demonstrate the performance of this circuit a bidirectional current source capable of linearly sourcing and sinking 10 mA into a 10 kΩ load was built using low-cost and widely available components. The demonstration circuit exhibited exceptional linearity and transient response inherent to the Howland topology without the use of specialized high-voltage integrated circuits.

The Howland current pump is a commonly used circuit employing an op amp and several resistors to perform voltage-to-current conversion. Monolithic difference amplifiers offer a convenient way to create a Howland current pump with excellent performance as is shown in Fig. 1. If the four on-chip resistors are of equal value, the relationship of the output current to the input voltage is:

$$V_{IN} = I_L(R_{OUT}) \rightarrow \frac{V_{IN}}{R_{OUT}} = I_L \quad (\text{Eq. 1})$$

The on-chip resistances in these difference amplifiers are closely matched allowing this topology to achieve extremely high output impedances^[1]. Unfortunately, this circuit has several practical limitations.

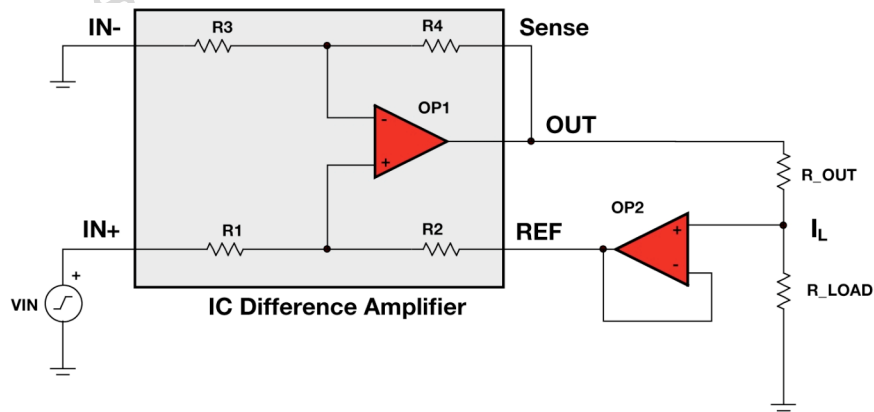


Fig. 1: Bidirectional Current Source Employing Monolithic Difference Amplifier

For low-impedance loads, the maximum difference amplifier output current is the dominant limitation of circuit performance. Surprisingly, for high-impedance loads, the difference amplifier output voltage range is the limiting factor. Current sources are not immune to Ohm's Law. Therefore, in order to drive a current through a load impedance, the circuit must be able to produce an appropriate voltage across the load. The range of output voltages a current source can produce at the load often is referred to as the compliance voltage. The maximum output current that the bidirectional current source in Fig. 1 can drive through a load impedance, when limited by its compliance voltage range, can be calculated:

$$I_{L(MAX)} = \frac{V_{LOAD(MAX)}}{R_{LOAD}} = \frac{V_{OUT(MAX)} \left(\frac{R_{LOAD}}{R_{LOAD} + R_{OUT}} \right)}{R_{LOAD}} \quad (\text{Eq. 2})$$

This may be a substantial limitation. Consider an IC difference amplifier powered by ± 15 V supplies that is able to drive its output voltage within 1.5 V of either supply rail. If the bidirectional current source employs an R_{OUT} of 1 k Ω (1 mA per volt input) and attempts to source current into a 10 k Ω load, then the maximum current the circuit can deliver is 1.23 mA.

$$I_{L(MAX)} = \frac{13.5V \left(\frac{10k\Omega}{10k\Omega + 1k\Omega} \right)}{10k\Omega} = 1.23mA \quad (\text{Eq. 3})$$

The result of Eq. 3 may be unexpected as the output current capability of the IC is often the intuitive limitation of a current source.

Parameters in Eq. 2 may be adjusted to increase the maximum output current into a high impedance load. Either the maximum output voltage or the load resistance ratio to the output resistance must be increased. While you can reduce the output resistance and compensate with gain in the feedback op amp, this approach is limited by the system's power supplies. In fact, because most monolithic difference amplifiers are designed to operate on supply rails less than 36 V, it seems that the circuit of Fig. 1 is incapable of delivering even modest currents into high-impedance loads.

Only a limited number of op amps and difference amplifiers are available to accommodate high-supply voltages and typically are very expensive. Fortunately, there is a well-documented method for operating op amps on wide supply rails known as bootstrapping^[2]. In a bootstrapped configuration, the output voltage of an op amp is used to directly control its supply voltages. Fig. 2 (overleaf) provides an example configuration where the voltage applied to the base of the npn and pnp transistors is determined by the output voltage as well as the ratio of the resistors R1 to R2 and R3 to R4.

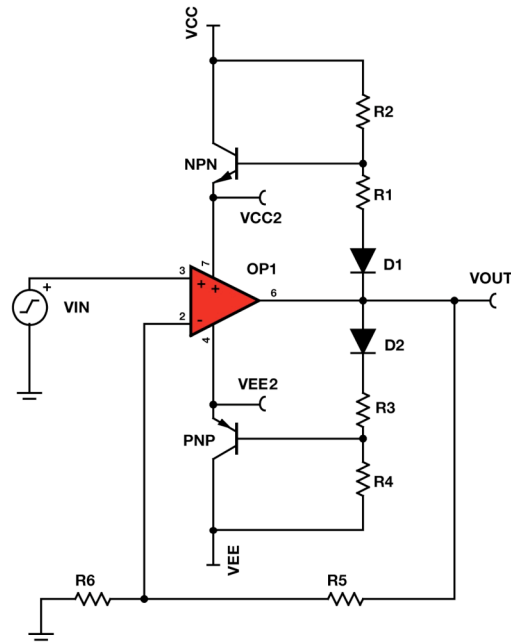


Fig. 2: Bootstrapping Op Amp To Allow Wide Supply Voltages

Diodes D1 and D2 compensate for the transistor V_{BE} drops. To simplify analysis, the transistor base current draw are ignored. This allows for the voltage at the op amp power supply pins to be calculated:

$$V_{CC2} = (V_{CC} - V_{OUT}) \frac{R_1}{R_1 + R_2} \quad (\text{Eq. 4})$$

There is one fundamental issue that prevents this approach from working in many applications: it is very easy to violate the op amp's input common-mode specifications. This is especially worrisome during system power-up where an asymmetrical ramp of the power supply voltages can cause the amplifier to latch.

With some slight modifications to the Howland topology, bootstrapping offers a very attractive way to increase the compliance voltage of bidirectional current sources. By replacing the op amp in Fig. 2 with a difference amplifier capable of an extremely wide input common-mode range, the risk of violating the system's input common-mode range is reduced. For example, the INA149 from Texas Instruments is capable of input common-mode voltages of ± 275 V, but does not use the standard difference amplifier topology. Thus, a slightly different circuit is necessary to produce the bidirectional current source transfer function previously presented.

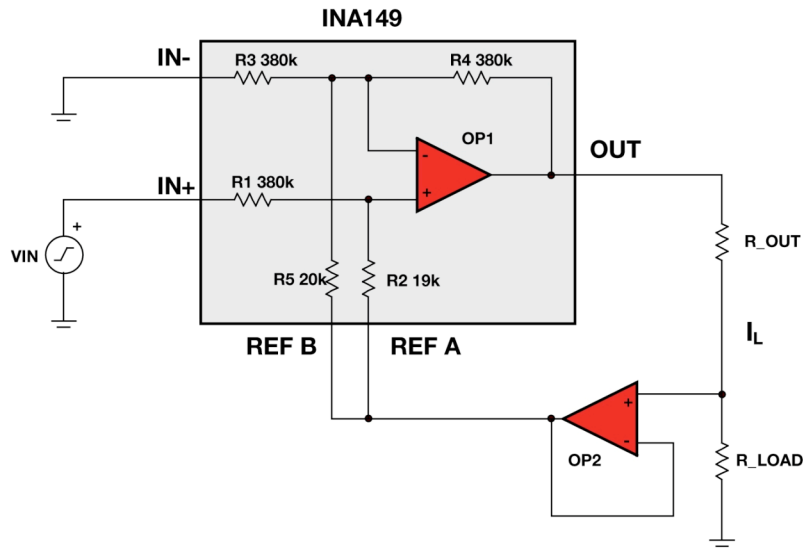


Fig. 3: Modified Bidirectional Current Source Topology Allowing Use Of Wide Common-Mode Voltage Difference Amplifiers

By bootstrapping the difference amplifier and feedback op amp supplies (Fig. 3), the circuit can be run on extremely high supply voltages, greatly increasing the amount of current it can deliver into high impedance loads.

Prototype Construction

In order to demonstrate the use of bootstrapping to extend the compliance voltage of a bidirectional current source, a prototype was constructed (see Fig. 4).

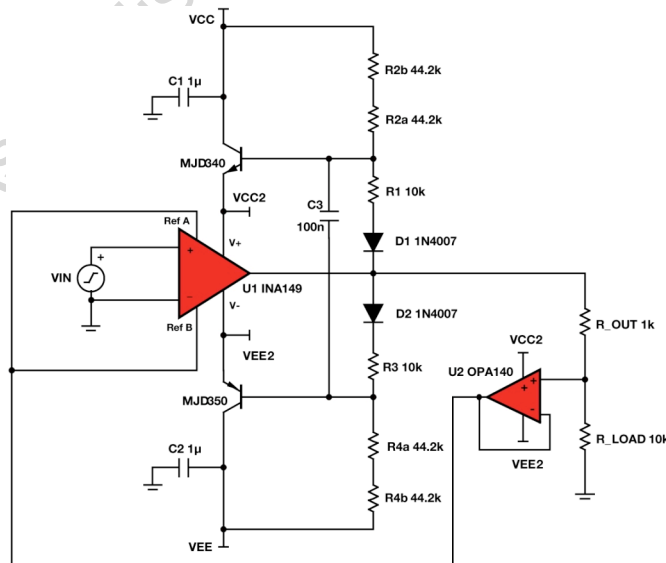


Fig 4.: Bootstrapping Increases Output Voltage Range

Fig. 4 illustrates the proper placement of decoupling capacitors in the circuit. C1 and C2 must be rated for high supply voltages, but C3 may have a voltage rating that only exceeds the nominal supply voltages of the difference amplifier. The prototype employed 450 V rated capacitors for C1 and C2, and a 50 V capacitor for C3. We constructed the circuit on a two layer PCB that incorporated large copper areas for dissipating heat from the transistors. The worst-case power dissipation in each transistor occurs if the circuit is required to drive the difference amplifier's maximum output current into a short circuit:

$$P_{BJT(WC)} = (V_{CC} - V_{CC2})I_{SC(INA149)} = (145V - 14.74V)25mA = 3.26W \quad (\text{Eq. 6})$$

This is significant and must be considered when constructing the circuit. We chose transistors in a surface-mount DPAK package to dissipate heat into copper areas on the PCB. This method for heat dissipation is preferred over discrete heat sinks for high-voltage safety reasons. The demonstration circuit board also incorporates multiple high-voltage safety warnings, and connectors that reduced the potential for unintended contact during testing. This circuit should only be constructed by engineers experienced with high voltage, and working in a laboratory environment equipped with proper safety measures.

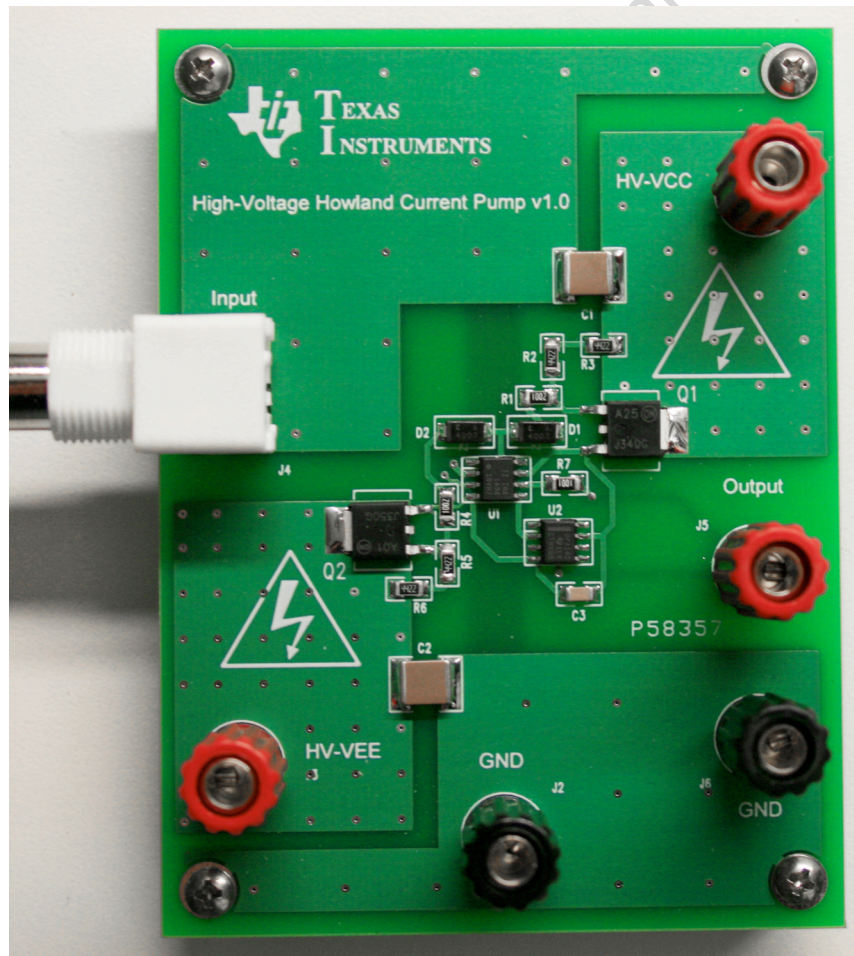


Fig. 5: Prototype Demonstrating High-Voltage Bidirectional Current Source

Performance

We investigated both the system's ac and dc performance characteristics using a precision 10 kΩ resistive load and powered the system with ±145 V supplies. For this bootstrapping topology, the power supply voltage across the difference amplifier decreases as the output voltage approaches either rail. You can estimate the maximum output current into the load by determining where the bootstrapped supply voltage approaches the minimum supply voltage for the part:

$$V_{CC} - V_{CC(MIN)} \frac{R_1 + R_{2a} + R_{2b}}{R_1} = V_{O(MAX)} \quad (\text{Eq. 7})$$

By inserting the values used in the prototype design and setting V_{CC2} equal to the minimum positive supply voltage of the difference amplifier (2V), you can estimate the circuit's maximum output voltage and, therefore, current:

$$145 - 2 \frac{10k + 44.2k + 44.2k}{10k} = 125.28 \text{ V} \quad (\text{Eq. 8})$$

$$I_{L(MAX)} = \frac{V_{OUT(MAX)} \left(\frac{R_{LOAD}}{R_{LOAD} + R_{OUT}} \right)}{R_{LOAD}} = \frac{(125.28) \left(\frac{10k}{10k + 1k} \right)}{10k} = 11.4 \text{ mA} \quad (\text{Eq. 9})$$

This estimate does not account for the reduced output current capabilities of the difference amplifier as the supply approaches its minimum value, or the effects of the reduced V_{CE} on the bootstrapping transistors, so is considered optimistic. To determine the actual maximum output current, the circuit's input voltage is swept while the output current through the load is monitored.

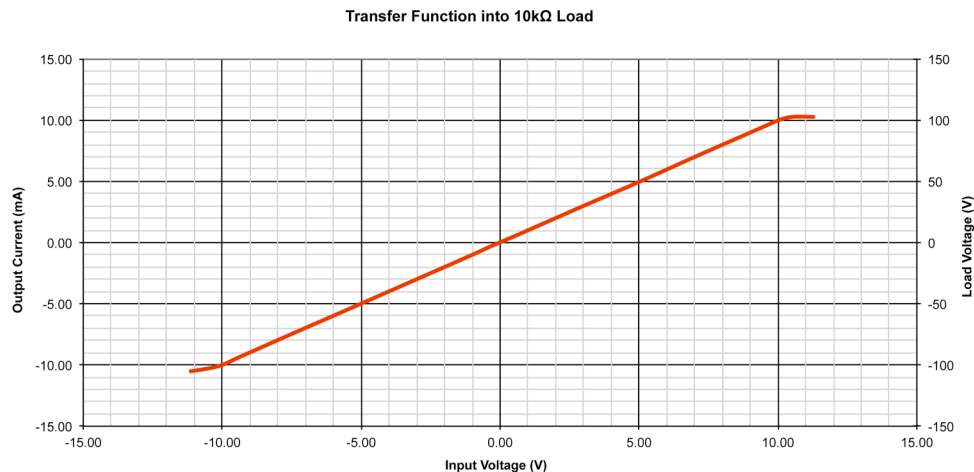


Fig. 6: Measured Transfer Function Of Bootstrapped Current Source Into 10 kΩ

The point where the output current ‘plateaus,’ or does not increase with increasing input voltage, can be considered the maximum output current. In Fig. 6, the maximum output current of the prototype circuit into a 10 kΩ load is 10 mA (both sourcing and sinking), an increase of a factor of 8.33 over the non-bootstrapped circuit previously calculated (Eq. 3). Note the circuit's extremely linear operation below the maximum output current.

The circuit's dynamic performance is equally impressive. Fig. 7 displays a ± 10 mA sinusoid being driven into a $10\text{ k}\Omega$ load at 50 kHz . This is the maximum frequency that the system is able to achieve its full output current into the $10\text{ k}\Omega$ load, indicating a maximum current slew rate of $3.14\text{ mA}/\mu\text{s}$. Put in more familiar terms, this is equivalent to a voltage slew rate of $31.4\text{ V}/\mu\text{s}$ at the $10\text{ k}\Omega$ load.

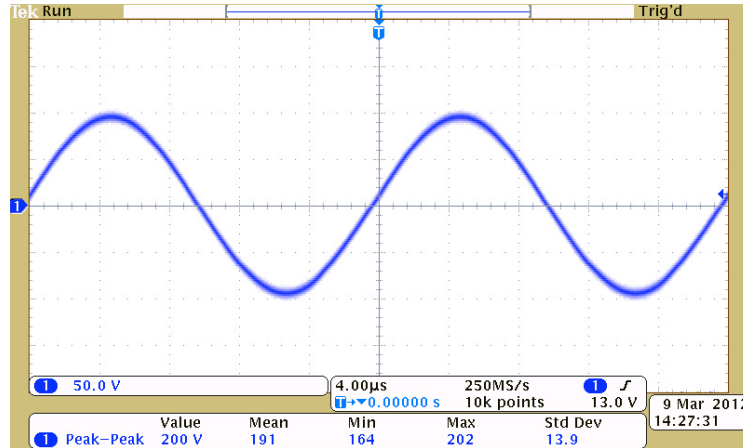


Fig. 7: 50 kHz Sine Wave Of ± 10 mA Amplitude Driving $10\text{ k}\Omega$ Load (200 Vp-p)

A ± 10 mA square wave is shown in Fig. 8. The waveform is devoid of any ringing that is indicative of stability issues and further illustrates the circuit's excellent transient response.

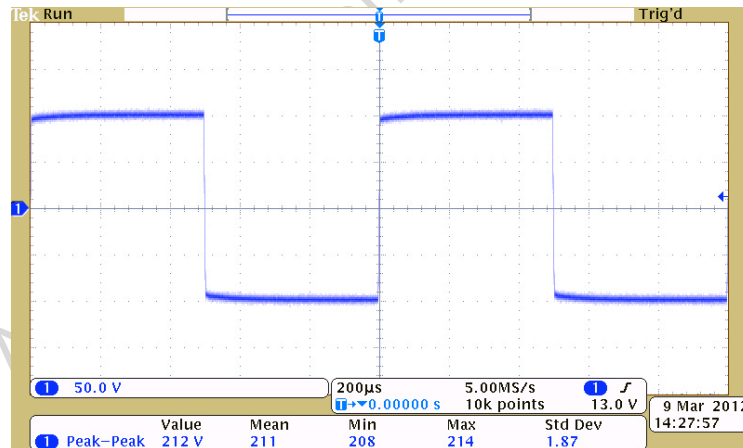


Fig. 8: 1 kHz ± 10 mA Square Wave Into $10\text{ k}\Omega$ Load (200 Vp-p) Devoid Of Ringing

Conclusion

This TechNote presents an approach to dramatically increase the compliance voltage range of difference amplifier-based bidirectional current sources. By employing a unique type of difference amplifier, such as the INA149, the circuit can be bootstrapped to very high supply voltages while still maintaining robust operation. A prototype was constructed to investigate the potential performance of this approach. The demonstration circuit operated on ± 145 V supplies and linearly drives up to ± 10 mA into a $10\text{ k}\Omega$ load at frequencies up to 50 kHz. The outstanding performance, simplicity and low cost of this approach makes it an attractive alternative to specialized high-voltage integrated circuits for developing bidirectional current sources capable of driving high-impedance loads.

References

1. Stitt, Mark, "[Implementation and Applications of Current Sources and Current Receivers](#)," Burr-Brown Application Bulletin, Texas Instruments, March 1990
2. King, Grayson; Watson, Tim, "[Bootstrapping your op amp yields wide output swings](#)," EDN, May 1999

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John Caldwell is an analog applications engineer for TI's Precision Analog Linear Applications group. John earned his MSEE and BSEE from Virginia Tech, Blacksburg VA. He has three pending patents and has published several papers. In 2009, John was a recipient of the coveted [Engibous Prize](#) in Texas Instruments Analog University Competition. John can be reached at ti_johncaldwell@list.ti.com



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