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Error compensation improves bipolar-current sinks

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You can improve a current sink's accuracy by at least two orders of magnitude by adding two standard 1%-tolerance resistors. As a bonus, you also compensate for errors that a low-current-gain pass transistor's base current introduces. To do so, you measure the transistor's base current and add a proportionally scaled error term to the source's reference voltage. When you design a current sink, you can use a MOSFET for the sink's pass transistor because of its nearly infinite power gain and low gate current. However, a high-power MOSFET presents high input and output capacitances that reduce the sink's high-frequency output impedance.

As an alternative, a low-current-gain, bipolar power transistor presents a much lower output capacitance than does a MOSFET of comparable power ratings. **Figure 1** shows a design for a bipolar-transistor-based current sink that unfortunately suffers from accuracy errors due to Q_1's base current's flowing into the current-measurement resistor R_1. The base current varies with changes in Q_1's collector current and current gain, which in turn depend on Q_1's production tolerances, junction temperature, and collector-emitter voltage.

You can use a Darlington transistor to increase the circuit's current gain and reduce the output error, but few Darlington transistors offer good high-frequency parameters. Superbeta power transistors are rare, have typically lower unity-gain-bandwidth frequencies, and are more expensive. In other words, even though a bipolar transistor presents higher output impedance at high frequencies, the error from its base current makes it a poor choice for a high-precision current sink. You could compensate for base-current errors by measuring the output transistor's collector current and introducing a correction factor, but that approach increases circuit complexity and reduces the sink's output impedance.

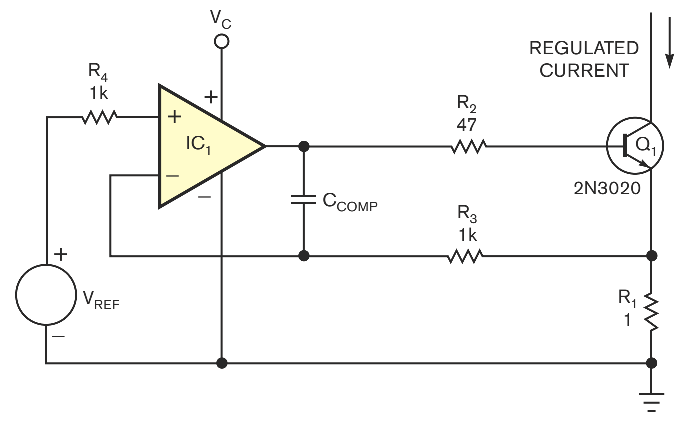

Figure 1 This typical quickly responding constant-current sink uses a bipolar transistor but suffers from base-current-induced error. Its nominal output current is $I_{OUT}=(V_{REF}/R_1)-I_B$.

Figure 2 shows a better approach, which adds a differential amplifier, IC_2, and resistors R_6 through R_9 to measure Q_1's base current by sampling the voltage across R_2. Resistors R_4 and R_5 scale and sum the error and reference voltages you apply to differential amplifier IC_1. Because IC_1's inverting input connects to current-shunt resistor R_1's upper end and not to ground, the reference voltage, V_{REF}, determines the error voltage applied to Q_1, preserving output scaling and allowing output-current calculation as V_{REF}/R_1. As a result, the regulated voltage across R_1 represents the sum of the desired output current plus the transistor's base current. Because the transistor inherently "subtracts" its base current, its collector current and, hence, the output current have no base-current error.

You can simplify the circuit and preserve its error-correction properties by combining IC_1 and IC_2; better yet, you can add two resistors to **Figure 1** to

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achieve the same effect. **Figure 3** shows the final circuit. To understand its operation, think of the circuit as a voltage regulator that delivers a voltage equal to V_{REF} across R_1. If you short-circuit base resistor R_2, note that any common-mode error that resistors R_5 and R_6 introduce cancels and thus has no effect on Q_1's base voltage. When you feed the voltage drop back to IC_1's input through R_5 and R_4, the voltage drop across R_2, representing Q_1's base current, increases the regulated voltage across R_1 by the ratio of R_5/R_4. If the ratio of R_5/R_4 equals that of R_2/R_1, the voltage across R_1 includes an error term that effectively cancels the base current. If $R_3=R_4$ and $R_5=R_6$, the following **equation** describes the output current, I_{OUT}:

$$I_{OUT} = \frac{V_{REF} + I_B \times R_2 \times \frac{R_4}{R_5}}{R_1} - I_B.$$

Because the base current, I_B, appears twice with opposite signs and cancels, the equation simplifies to: $I_{OUT}=(V_{REF}/R_1)$.

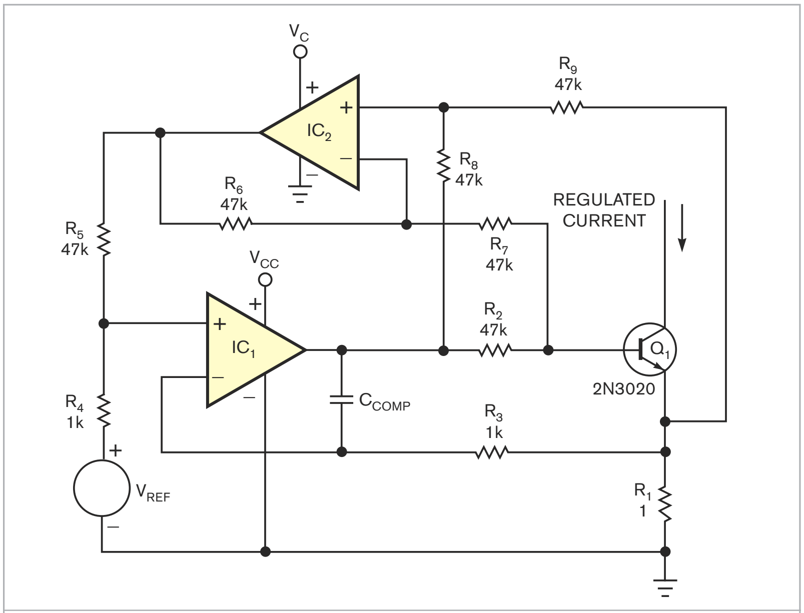

Figure 2 Adding base-current error compensation improves the circuit's performance. Using perfectly matched resistors simplifies the output-current equation to $I_{OUT}=(V_{REF}/R_1)$.

To optimize the circuit's performance, use the following resistor ratios: $R_2/R_1=R_5/R_4$, $R_5=R_6$, $R_3=R_4$, $R_5>>R_4$, and $R_3>>R_1$. Using standard 1%-tolerance resistors in the circuit of **Figure 3** reduces the error from Q_1's base current to about one-one-hundredth of its uncompensated level. Without compensation, a low-gain power transistor with a typical current gain of 25 at Q_1 would introduce a full-scale current error of 4%. The circuit corrects the error to 0.04% and raises Q_1's current gain to an effective current gain of 2500. Perfect matching would result in an immeasurably small base-current error. Note that IC_1's input common-mode-voltage range must include the negative-supply-voltage rail. Equal resistances at both of IC_1's inputs balance the op amp's input-bias currents. The minimum power-supply voltage depends on IC_1's maximum current-sourcing capability and on the sum of the worst-case voltage drops across Q_1's base-emitter junction, R_1 and R_2. The circuit's maximum output current depends on Q_1's worst-case minimum current gain times IC_1's worst-case minimum output current.

To ensure stable operation, use a unity-gain-stable op amp for IC_1. When the circuit operates within its nominal current range, an op amp whose response time is substantially

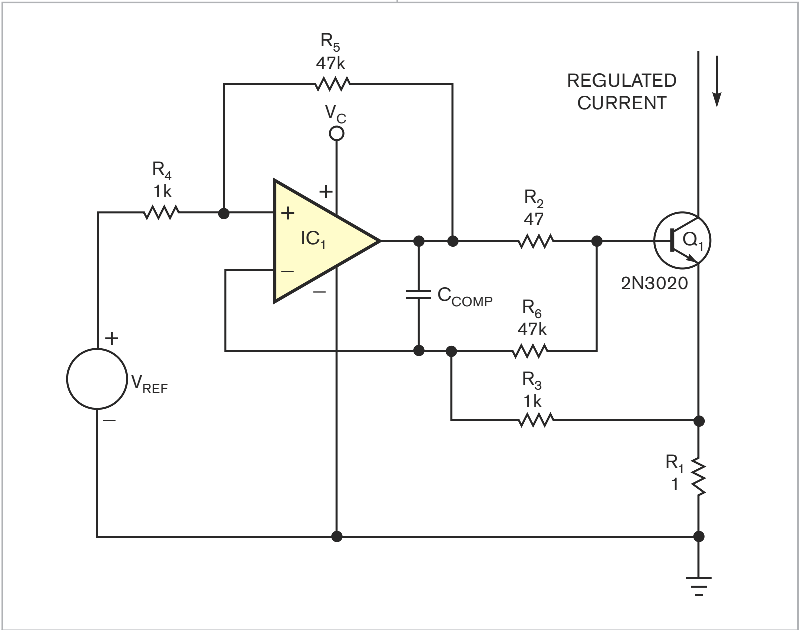

Figure 3 You can further simplify the current sink's design by adding only two resistors, R_5 and R_6, to the original in Figure 1. The output-current equation remains $I_{OUT}=(V_{REF}/R_1)$, as in Figure 2.

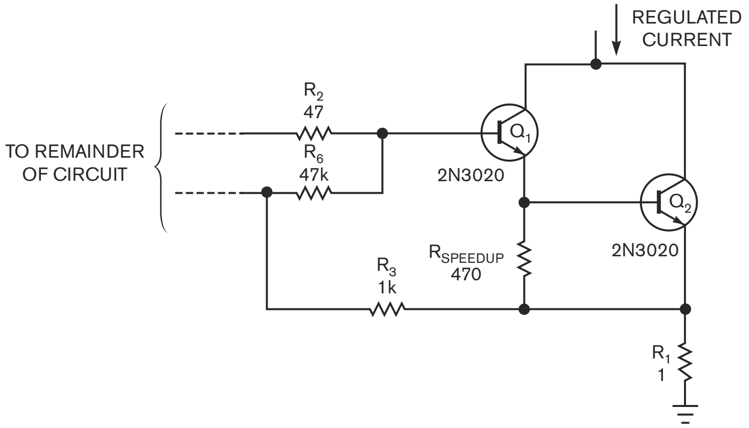

Figure 4 Adding $R_{SPEEDUP}$ improves the performance of a two-transistor Darlington output stage.

longer than Q_1's generally doesn't require installation of compensation capacitor C_{COMP}. However, a small capacitor of a few tens of picofarads guarantees stability under all conditions—for example, when the circuit's output current and the feedback voltage across R_1 approach zero.

The circuit in **Figure 3** works equally well if you use a Darlington transistor for Q_1 because its higher current gain further improves the circuit's operation. If you use two discrete bipolar transistors, you can improve the composite Darlington transistor's turn-off time by connecting a resistor between the output transistor's base and emitter to remove its excess base charge (**Figure 4**).

You can use either a fixed or an adjustable reference-voltage source, but for the smallest possible error, the reference source's output impedance should be fairly low to sink feedback current from R_4. You can also proportionally increase the values of resistors R_3 through R_6 to reduce the amount of current that the reference source absorbs. It's amazing what you can achieve by adding only two resistors to an already-simple circuit.**EDN**