A User-Proof Connection to an Internal Supply: a Simple Current-Limited Output

Circuit 2: The Improved One-BJT Current Limiter

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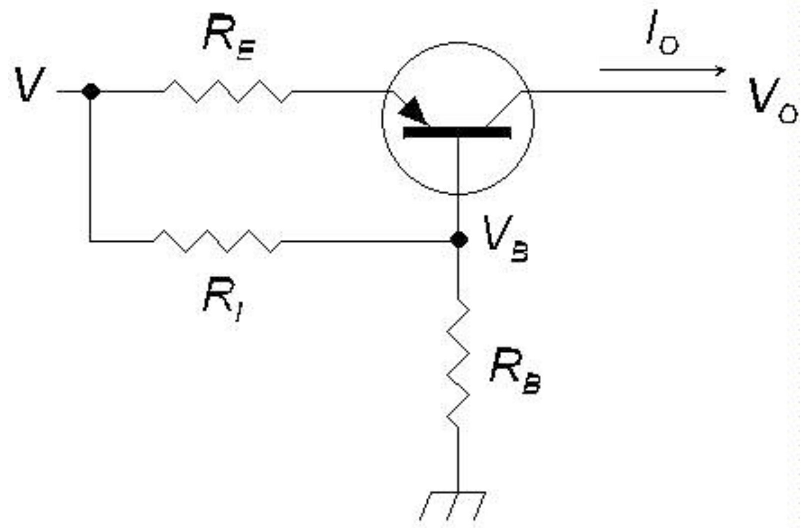
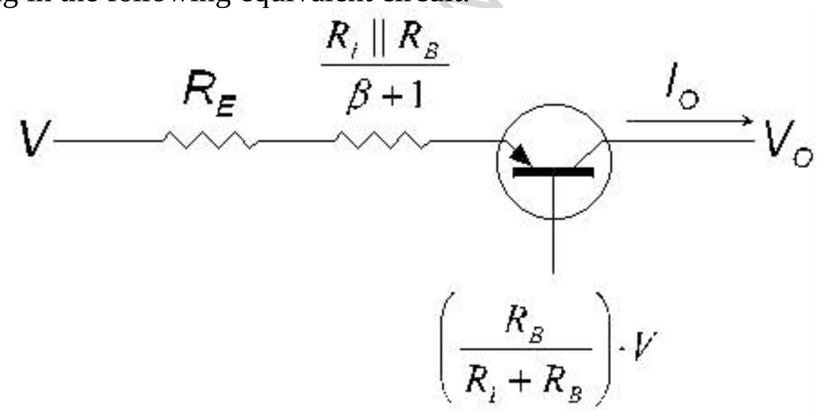
The improved one-BJT current-limiting supply is not much different than the primitive circuit, though its one additional resistor does change the circuit behavior. The improved circuit is shown below.



Analysis quickly proceeds by Thévenizing the base circuit and β-transforming the Thévenin base resistance to the emitter, resulting in the following equivalent circuit.



When the BJT is not saturated, the output current is a maximum of:

$$I_O = \alpha \cdot \frac{V - V_{EB}(\mathrm{sc}) - \left(\dfrac{R_B}{R_i + R_B}\right)\cdot V}{R_E + \dfrac{R_i \parallel R_B}{\beta + 1}} = \alpha \cdot \frac{\left(\dfrac{R_i \parallel R_B}{R_B}\right)\cdot V - V_{EB}(\mathrm{sc})}{R_E + \dfrac{R_i \parallel R_B}{\beta + 1}}$$

where, $V_{BE}(I_O) = V_{BE}(\mathrm{sc})$.

Under light load, the BJT saturates and as with the previous circuit, $V_{CB}(\mathrm{oc}) \approx V_{EB}(\mathrm{oc})$ and:

$$V_O = V_B + V_{EB}(\mathrm{oc}) = \left(\frac{R_i \parallel R_B}{R_i}\right)\cdot V + V_{EB}(\mathrm{oc})$$

where, $V_{EB}(\mathrm{oc})$ corresponds to the minimum-current value. In the previous circuit this was $V_{EB}(\mathrm{oc}) = 0.50$ V at 1.3 μA.

To design, choose R_B. Its choice is subject to the constraint that $R_E \geq 0\ \Omega$:

$$R_B \leq \frac{\beta}{I_O} \cdot \left(V - \frac{V_{EB}(\text{sc})}{\left(\dfrac{V - V_O + V_{EB}(\text{oc})}{V_O - V_{EB}(\text{oc})} \right)} \right)$$

Then solve for R_i from the V_O equation:

$$R_i = R_B \cdot \left(\frac{V - V_O + V_{EB}(\text{oc})}{V_O - V_{EB}(\text{oc})} \right)$$

Finally, from the I_O equation, find:

$$R_E = \alpha \cdot \left[\left(\frac{V}{I_O} - \frac{R_B}{\beta} \right) \cdot \left(\frac{V - V_O + V_{EB}(\text{oc})}{V_O - V_{EB}(\text{oc})} \right) - \frac{V_{EB}(\text{sc})}{I_O} \right]$$

Dependence of I_O on β is minimized when $\partial I_O/\partial\beta$ is minimum, or whenever $R_E >> (R_i \| R_B)/(\beta + 1)$. This compares with what was found for the primitive one-BJT circuit. For this circuit, R_i makes the inequality easier to satisfy.

Test Circuit

To test these equations, a design was carried out and built for I_O = 20 mA using a 2N2907 BJT selected for a β of 150. The V_{EB} were calculated using $I_S = 5\text{ fA} = 5 \cdot 10^{-15}$ A. I_S is difficult to obtain directly from the $V_{BE}(I_C)$ curves in the parts data because those curves are not exactly exponential. They include the additional linear voltage contribution of the series resistance of r_e', the ohmic emitter resistance, and r_b', the ohmic base resistance, referred to the emitter. Additional calculation from the curves leads to the conclusion that the total effective ohmic emitter resistance is about 0.5 Ω. If the V_{BE} are calculated from the given I_S then the values will be somewhat low, especially for the high-current value. The easiest and most accurate procedure for design is to read the two pairs of numbers off the V_{BE} curves.

The values used in this design were:

$$V_{BE}(\text{sc}) = 0.749\text{ V}, 20\text{ mA}$$

$$V_{BE}(\text{oc}) = 0.53\text{ V}, 5\text{ ìA}$$

The resistor values calculate from the design formulas to be:

R_E = 33 Ω, R_i = 1.2 kΩ, R_B = 2.7 kΩ

The circuit was built with these standard ±5% parts values but this time a $1000 DMM (a Keithley 2000) was used to go through the 5% resistor parts bins and select parts within about 0.1% of these nominal values. Then:

$$R_B \| R_i = 830.8\ \Omega$$

and:

$$\frac{R_B \| R_i}{\beta + 1} = 5.5\ \Omega < R_E$$

β dependence is reduced with R_E six times that of the base-referred resistance, showing the role of R_i. Also:

$$\left(\frac{R_B}{R_i + R_B}\right) \cdot V = 3.475 \text{ V}$$

The base divider was disconnected and the measured voltage agreed with the above value in all digits. Then the $30 (DT-182) DMM was used to measure output current by placing it as an ammeter across the output, effectively shorting it. The DMMs were both used to measure voltages, and the following values resulted.

R_L, Ω	V_B, V	V_E, V	Calculated V_{BE}, V	Calculated I_E, mA	V_O, V	I_O, mA	Measured with
∞	4.25	4.94	0.69	1.01	4.92	0	DT-182
1 M	4.30	4.988	0.69	0.97	–	$\approx 5 \cdot 10^{-3}$	Keithley 2000
0	3.55	4.28	0.73	22.4	0	20	DT-182
0	3.59	4.32	0.73	21.2	0	21	Keithley 2000

The measured value of V was 5.00 V. The measured values of I_O appear to verify the design equations.

This improved one-BJT current-limited source is not a bad choice for a low-cost, low-parts-count current limiting supply extender. The value of I_O, unlike the carefully value-selected prototype above, will have a spread of values corresponding to parts tolerances, including BJT β. Many less-demanding applications can be satisfied by it.

By adding one more transistor, some additional improvement can be realized, the topic we consider next.