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

Circuit 3: Two-BJT Current Limiter

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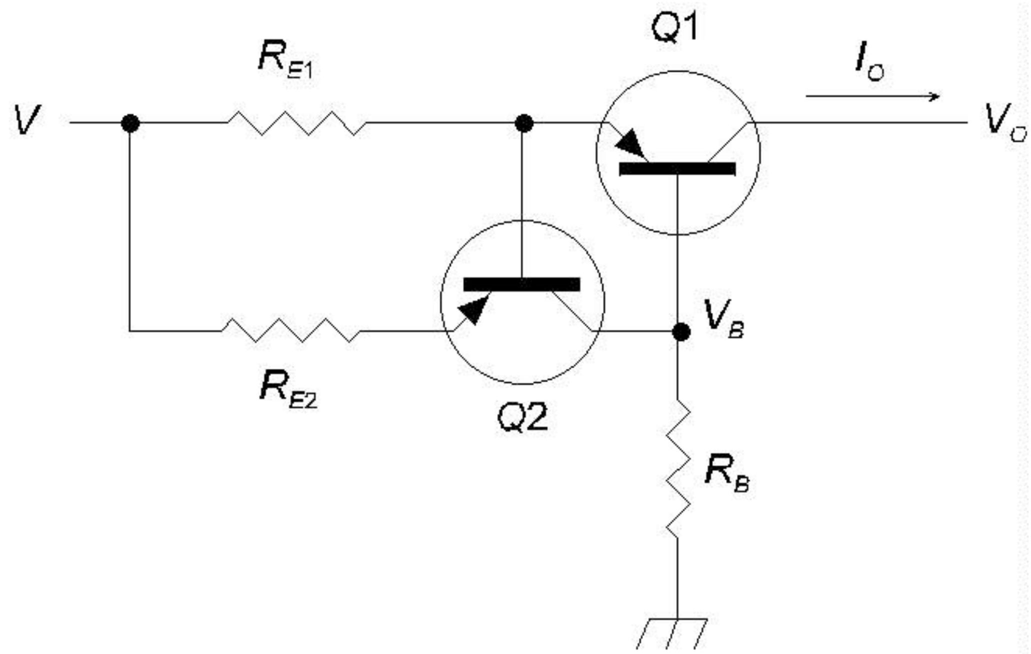
Some additional improvement in circuit performance can be achieved over the improved one-BJT current-limited supply by adding one transistor, $Q2$, as shown below. R_i of the previous circuit now becomes R_{E2} of $Q2$.



The basic idea is that as current through R_{E1} increases, the resulting increased voltage drop across R_{E2} will increase current in R_B and increase V_B, thereby limiting I_{E1}. This simple 5-component circuit is not trivial to analyze because of the tight interaction of the two BJTs.

Analysis is simplified by the observation that the emitter current of $Q1$ consists of two components: the currents of R_{E1} and I_{B2}. The base current of $Q1$ has both components, and I_{B1} from I_{B2} is $I_{B2}/(\beta_1 + 1)$ or $I_{C2}/\beta_2 \cdot (\beta_1 + 1)$. This current and I_{C2} flow through R_B to contribute to V_B and they are proportional, through the β values. Yet the I_{B1} component is very small compared with I_{C2}, by a ratio of $1/\beta_2 \cdot (\beta_1 + 1)$. The total current in R_B caused by $Q2$ is:

$$\left(1 + \frac{1}{\beta_2 \cdot (\beta_1 + 1)}\right) \cdot I_{C2}$$

For a typical β value of 150, the β factor is $44.15 \cdot 10^{-6}$ or 44 ppm. Analysis is simplified by making the approximation that this current is negligible, and omitting it. This is equivalent to having $\beta_2 \to \infty$. Then $I_{B2} = 0$ A. Once we know about this $1/\beta_2 \cdot (\beta_1 + 1)$ factor, it is not hard to put it back into the subsequent equations to make them exact, as we shall see. Again, the same design goals hold as for the previous circuits.

Circuit Analysis

Electronics would be less enjoyable without circuit analysis. It is a concomitant dual of design. Once we have a prospective circuit, we must first analyze it before we can best determine how to optimize its design. Hence, a few circuit equations are in order, beginning with the variable that is the functional result of the circuit, the output current:

$$I_O = I_{C1} = \beta_1 \cdot I_{B1} = \alpha_1 \cdot I_{E1}$$

The base voltage of $Q1$ is somewhat more involved:

$$V_B = R_B \cdot (I_{B1} + I_{C2}) = R_B \cdot \left(\frac{I_{E1}}{\beta_1 + 1} + \beta_2 \cdot I_{B2} \right)$$

Now I_{E1}, as previously noted, has a I_{B2} component that can be separated:

$$V_B = R_B \cdot \left(\frac{I_{B2} + \dfrac{V - V_{EB1} - V_B}{R_{E1}}}{\beta_1 + 1} + \beta_2 \cdot I_{B2} \right)$$

Grouping the I_{B2} terms together:

$$V_B = R_B \cdot \frac{V - V_{EB1} - V_B}{(\beta_1 + 1) \cdot R_{E1}} + R_B \cdot \left(\beta_2 + \frac{1}{\beta_1 + 1} \right) \cdot \left(\frac{V - V_{EB1} - V_{EB2} - V_B}{(\beta_2 + 1) \cdot R_{E2}} \right)$$

The last factor of the last term is:

$$I_{B2} = \left(\frac{V - V_{EB1} - V_{EB2} - V_B}{(\beta_2 + 1) \cdot R_{E2}} \right)$$

To simplify notation, let:

$$V_1 = V - V_{EB1}$$

Then when the above equation is solved for V_B:

$$V_B = \frac{G_1 \cdot V_1 + G_2 \cdot (V_1 + V_{EB2})}{1 + G_1 + G_2}$$

where:

$$G_1 = \frac{R_B}{(\beta_1 + 1) \cdot R_{E1}}, \quad G_2 = \alpha_1 \cdot \frac{R_B}{R_{E2}} \cdot \left(1 + \frac{1}{\beta_2 \cdot (\beta_1 + 1)} \right) = \alpha_1 \cdot \frac{R_B}{R_{E2}}, \ \beta_2 \to \infty$$

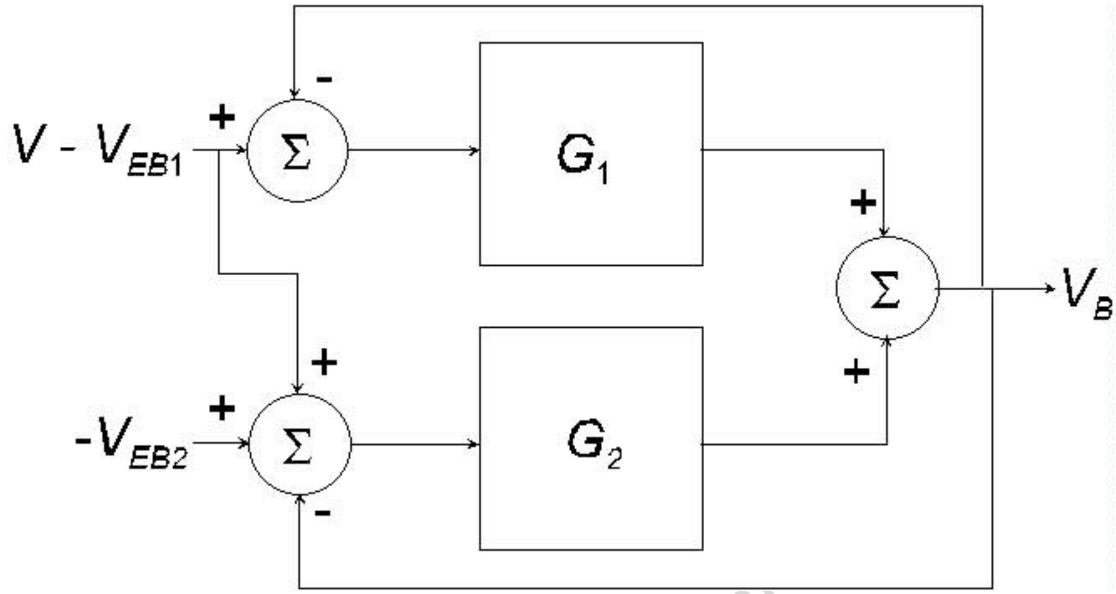
Then V_B simplifies to:

$$V_B = \frac{(G_1 + G_2) \cdot V_1 - G_2 \cdot V_{EB2}}{1 + (G_1 + G_2)} = \frac{G \cdot V_1 - G_2 \cdot V_{EB2}}{1 + G}$$

where:

G = G1 + G2

This has the form of a feedback equation with additive forward-path gains G_1 and G_2, and a feedback-path gain of $H = 1$. This can be cast in the form of a feedback block diagram as shown below. Two input quantities contribute to V_B.



Knowing V_B, we can now expand the I_O equation as $I_{E1} = I_O/\alpha_1$:

$$\frac{I_O}{\alpha_1} = I_{E1} = \frac{V_{RE1}}{R_{E1}} + \frac{V_{RE1} - V_{EB2}}{(\beta_2 + 1)\cdot R_{E2}} = \frac{(V - V_{EB1}) - V_B}{R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2}} - \frac{V_{EB2}}{(\beta_2 + 1)\cdot R_{E2}}$$

Then

$$\frac{I_O}{\alpha_1} = \frac{V - V_{EB1}}{R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2}} \cdot \left(1 - \frac{G}{1+G}\right) + \frac{1}{R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2}} \cdot \left(\frac{G_2}{1+G}\right)\cdot V_{EB2} - \frac{V_{EB2}}{R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2}}$$

$$= \frac{V - V_{EB1}}{(1+G)\cdot(R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2})} + \left(\frac{G_2}{1+G}\cdot\frac{1}{R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2}} - \frac{1}{R_{E1} \,||\, (\beta_2 + 1)\cdot R_{E2}}\right)\cdot V_{EB2}$$

Using the $I_{B2} = 0$ A approximation, this simplifies to:

$$\frac{I_O}{\alpha_1} \approx \frac{(V - V_{EB1}) + G_2 \cdot V_{EB2}}{(1+G)\cdot R_{E1}}, \ \beta_2 \to \infty$$

Also:

$$I_{E2} \approx \frac{(V - V_{EB1}) - (1+G_1)\cdot V_{EB2}}{(1+G)\cdot R_{E2}}, \ \beta_2 \to \infty$$

Measured Results For Two-BJT Circuit

These equations were tested by setting $Q1$ = 2N2907 with $\beta_1 = 150$, $Q2$ = 2N2907 with β_2 large ($\beta_2 \to \infty$ assumption), $R_{E1} = 20.0\ \Omega$, 1%, $R_{E2} = 1.0\ \text{k}\Omega$, 5%, and $R_B = 3.3\ \text{k}\Omega$, 5%. The goal of the design was $I_O = 60$ mA and $V_O \geq 3.5$ V. With BJT $I_S \approx 5$ fA, then $V_{EB1} = 0.50$ V atr 1.3 μA.

The gain values were calculated as:

$$G_1 = \frac{R_B}{(\beta_1 + 1)\cdot R_{E1}} = \frac{3.3\,\text{k}\Omega}{(151)\cdot(20.0\,\Omega)} = 1.0927$$

$$G_2 \approx \alpha_2 \cdot \frac{R_B}{R_{E2}} = 3.2781$$

and $G = G_1 + G_2 = 4.3709$

The output current then calculates to be:

$$I_O = \alpha_1 \cdot \frac{(V - V_{EB1}) + G_2 \cdot V_{EB2}}{(1+G)\cdot R_{E1}} = (0.993)\cdot \frac{(5\,\text{V} - 0.78\,\text{V}) + (3.2781)\cdot V_{EB2}}{(5.371)\cdot(20.0\,\Omega)}$$

Also:

$$I_{E2} = \frac{(V - V_{EB1}) - (1+G_1)\cdot V_{EB2}}{(1+G)\cdot R_{E2}} = \frac{4.22\,\text{V} - (2.0927)\cdot V_{EB2}}{(5.371)\cdot(1.0\,\text{k}\Omega)}$$

Iterating I_{E2} to obtain both it and V_{BE2}, then V_{BE2} = 0.655 V and I_{E2} = 0.534 mA. Then:

IO = α2·(39.44 mA + 20 mA) = 59.0 mA

and:

$$V_B = \frac{G\cdot(V - V_{EB1}) - G_2 \cdot V_{EB2}}{1+G} = 3.048\,\text{V}$$

Two copies of the circuit were built and measurements were taken, given in the following table.

Measurements	**Unit 1**		**Unit 2**	
R_L, Ω	**V_O, V**	**I_O, mA**	**V_O, V**	**I_O, mA**
∞	4.97	0	4.97	0
294	4.61	15.7	4.58	15.6
110	4.13	37.2	4.09	36.8
≈ 0	0.11	58.4	0.12	63.0

For 5% resistors, the agreement is sufficiently convincing.

Design Procedure

The equations from circuit analysis can now be put into a form useful for design, as a procedure.

Given:

IO(sc) = IO; VO(oc) = VO; V, Q1, Q2 with their VEB1, VEB2 at IO,

$V_B = V_O + V_{EB1}$ For $Q1$, $Q2$ matched (same type transistor), then:

$V_{EB2} \approx V_{EB1} - V_T \cdot \ln(I_{E1} / I_{E2})$

For V_{EB} cancellation in I_O (of the effects of V_{EB1} and V_{EB2}), then $V_{BE1} = G_2 \cdot V_{BE2}$. This is a design optimization constraint leading to:

$$G_1 = \frac{R_B}{(\beta_1 + 1) \cdot R_{E1}}$$

$$G_2 = \frac{V_{BE1}}{V_{BE2}} = \frac{R_B}{R_{E2}}$$

$$G = \frac{V_B + V_{EB1}}{V - (V_B + V_{EB1})}$$

and:

$$G1 = G - G2$$

Then calculate:

$$R_{E1} = \frac{V}{(1+G) \cdot (I_O / \alpha_1)}$$

and:

$$R_B = G_1 \cdot (\beta_1 + 1) \cdot R_{E1}$$

from which the final resistor value is:

$$R_{E2} = \frac{R_B}{G_2}$$

Then:

$$V_B = \frac{G}{1+G} \cdot V - \frac{G_1}{1+G} \cdot V_{EB1}$$

and:

$$I_{E2} = \frac{(V - V_{EB1}) - V_{EB2} - V_B}{R_{E2}}$$

Finally:

$$I_O = \alpha_1 \cdot \frac{V}{(1+G) \cdot R_{E1}}$$

Non-Feedback Equivalent Circuit

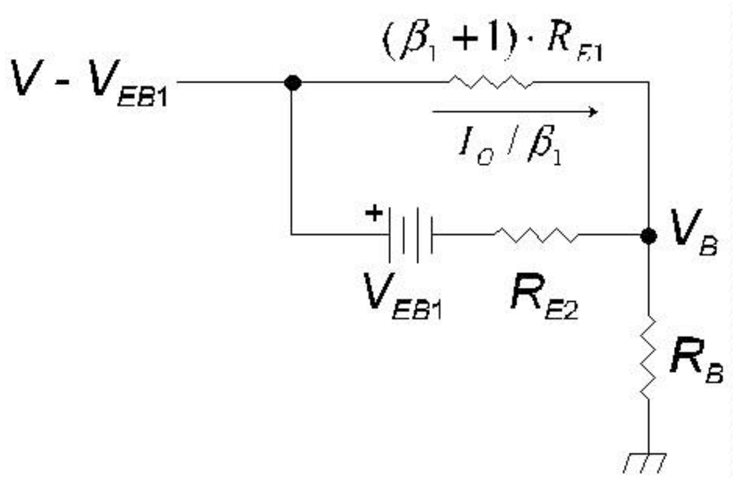
A simpler equivalent circuit can be derived that does not involve feedback by using the β transform to refer R_{E1} to the base side of $Q1$ and by noting that because the feedback gain, $H = 1$, that this is equivalent to placing R_{E2} in parallel with R_{E1} as shown below. This circuit can be reduced to a resistive voltage divider, as shown in the lower diagram. V_{EB1} is moved left to join V. Then R_{E1} is referred to the base of $Q1$. $Q2$ is assumed to have $\beta_2 \to \infty$ so that $\alpha_2 = 1$. Then $I_{C2} = I_{E2}$. The voltage across R_{E1} is the same as that across the base-referred R_{E1} and the two resistances are in parallel, connecting to the base on the right side. Some Thévenizing produces the equivalent circuit of the lower diagram. Because this is a base circuit, the current is I_O/β_1, and I_O can be readily calculated from it. The result is identical to the approximated expression derived previously.

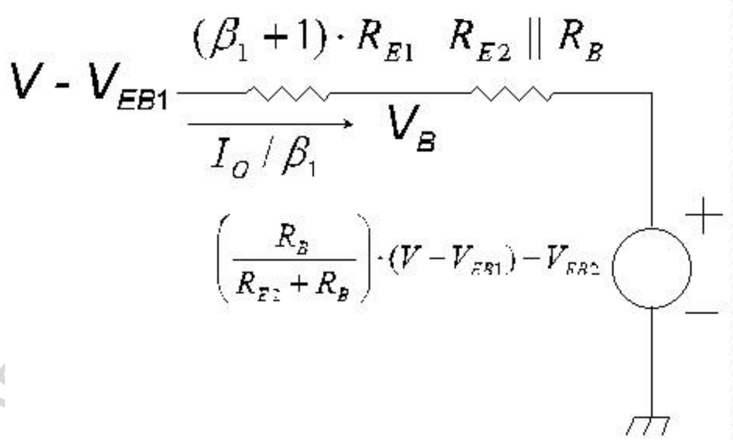
It is perhaps even more evident in this circuit form that for β_1 insensitivity that $R_{E2} << (\beta_1 + 1) \cdot R_{E1}$ and that consequently it must be maintained that $G_2 >> G_1$, or that $G >> G_1$. Then:

$$I_O \approx \alpha_1 \cdot \frac{V}{(1+G) \cdot R_{E1}}$$

where:

$$G = \frac{R_B}{R_{E2} \parallel (\beta_1 + 1) \cdot R_{E1}}$$





Closure

Three variations of simple current-limiting circuits have been presented. These circuits can find use wherever a maximum current must be specified while also maintaining a minimum output voltage up to near the current-limit value. How near was not derived but some idea is given in the measurements for the two-BJT circuit. While not trivial to analyze (except perhaps the first), these circuits have less than a half dozen parts and less than a dozen cents US in cost in small quantity. The design procedures have been given, and for the two-BJT circuit, two equivalent-circuit interpretations. Hopefully, you should be able to apply any of them in your designs where appropriate.