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

Circuit 1: The Primitive One-BJT Current Limiter

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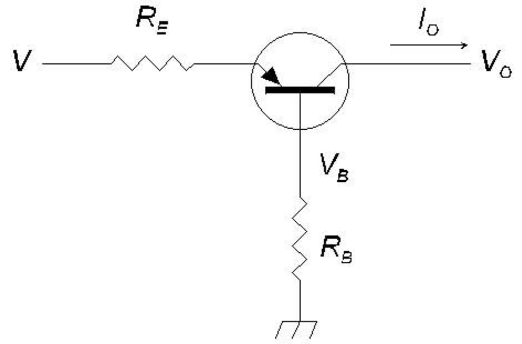
Ordinary power supply design includes current limiting as a protection feature. In product design, this is usually sufficient in that the engineer decides the loads on the supply by design. However, in some applications a supply must be brought outside the box where it enters the realm of the user. Examples include sensor bridge and solid-state relay (SSR) supplies for data acquisition systems and USB power of computer peripherals. There are multiple commercial products for protected USB supplies but these are not always optimal for non-USB applications.

This article presents three simple circuits that can drive a current-limited supply port intended for use by a potentially terminal-shorting user. The design goal is a circuit that has a maximum short-circuit current by design so that this amount of current can be budgeted in the design of its internal supply. They also use fewer than half a dozen parts and are very low in cost.

Primitive One-BJT Circuit

The first circuit is primitive but provides a conceptual place to start. It is shown below.



Following the general scheme used in low-dropout linear regulators, this circuit uses a pnp BJT to pass current to the output. One transistor and two resistors is simple, but the behavior is limited. The maximum, short-circuit output current is calculated by applying the β transform to the base resistance, R_B, placing it in the emitter as $R_B/(\beta + 1)$ along with R_E. Then at most:

$$I_O = \alpha \cdot \frac{V - V_{BE}}{R_E + R_B/(\beta + 1)}$$

For a 2N2907, $V_{BE} \approx 0.78$ V at an I_O design maximum of 60 mA, and a typical $\beta = 150$. Using an internal 5 V supply, $V = 5$ V. We have two resistor values to choose and one constraint equation, allowing us to apply another constraint. The output voltage is affected by choice of both resistors. The larger R_B is made, the higher the voltage. Ideally, $V_O = V$, but to power SSRs, at least 3 V is needed. Then:

$$V_O \approx V_B + V_{BE}$$

or:

$$V_B \approx V_O - V_{BE}$$

assuming $V_{EB} \approx V_{CB}$ when the BJT is in saturation.

The output voltage, V_O, for light loads in saturation is:

$$V_O \cong V - I_O \cdot R_E$$

assuming ideal voltage saturation of the BJT so that $V_{CE} = 0$ V.

In practice, V_{CE} can typically be from 10 to 50 mV.

For those desiring greater detail, collector open-circuit voltage, with $I_C = 0$ A, is:

$$V_{CE} = V_T \cdot \ln\left(\frac{1}{\alpha_R}\right), I_C = 0\text{ A}$$

The thermal voltage, $V_T \approx 26$ mV at 300ºK (tropical room temperature) and the reverse α, or α_R, is that of the BJT operated with emitter and collector exchanged from their normal or *forward* configuration.

Collector and emitter junctions are *not* symmetrical for any well-designed transistor and the minority carrier doping level of the emitter is much higher than collector (for high emitter injection efficiency and high collector-base voltage breakdown). Reversing the BJT results in low β_R values. A random selection of 2N2907s from the parts drawer, plugged into the "h_{FE}" function on a low-cost DMM, resulted in values of 2, 4, 8, and 13. Choosing a low value as $\beta_R = 2$, then a low $\alpha_R = 2/3 \approx 0.67$, a value well below one. Then V_{CE} at zero collector current is about 10.5 mV.

If we choose a very light load of 1.3 μA as a zero-scale value – about what a low-cost DMM will draw when measuring V_O – then, at 1.3 μA, $V_{BE} = 0.50$ V. ($I_S \approx 5$ fA for a 2N2907.) However, under light load the BJT is in saturation and β is much less than the non-saturated value and is determined by circuit constraints. Therefore, only the minimum value of R_B is of concern. As load demand for current increases, current is diverted from base to collector until the transistor comes out of saturation and has its normal $\beta = \beta_F$. When V_O has decreased to V_B, $V_{CE} = 0$ V and the BJT is out of saturation. Then load current must be near the maximum. For 60 mA, $V_{BE} = 0.78$ V and I_B for minimum $\beta = 100$ is 600 μA. Consequently $R_B < 4.16$ kΩ.

With $V_{BE}(I_O)$ at 0.78 V, to make the voltage at which the BJT unsaturates as high as possible, then all the resistance should be in R_B and none in R_E. The problem with this is that now (referring to the I_O formula) I_O is most β-dependent. With a wide range of β values among manufactured parts (of 100 to 300 for a 2N2907), it would be best to make R_B as small as the voltage constraint will allow and maximize R_E:

$$R_B \approx \frac{V_O(\text{min}) - V_{EB}(I_O)}{\left(\dfrac{I_O}{\beta_1(\text{min})}\right)} = \frac{3\text{ V} - 0.78\text{ V}}{60\text{ mA}/100} = 3.70\text{ k}\Omega \Rightarrow 3.6\text{ k}\Omega, 5\,\%$$

Then:

$$R_E = \frac{V - V_O(\text{min})}{I_O/\alpha} = \frac{5\text{ V} - 3\text{ V}}{60\text{ mA}/0.993} = 33.11\,\Omega \Rightarrow 33\,\Omega, 5\,\%$$

The conflicting criteria between maximizing V_O and β independence make the circuit rather unappealing. However, for a wide tolerance on I_O and V_O, it suffices with three parts. The basic design equations could be refined for a specified tolerance range for β, but instead we will move along to the next, slightly improved circuit having one additional resistor.