

# Power Tips: How to Design a Robust Series Linear Regulator with Discrete Components



Manjing Xie

There are applications that require loose output regulation and current less than 20mA. For such applications, a linear regulator built with discrete components is a cost-effective solution (Figure 1). For applications with tight output regulation and requires more current, a high performance LDO can be used.

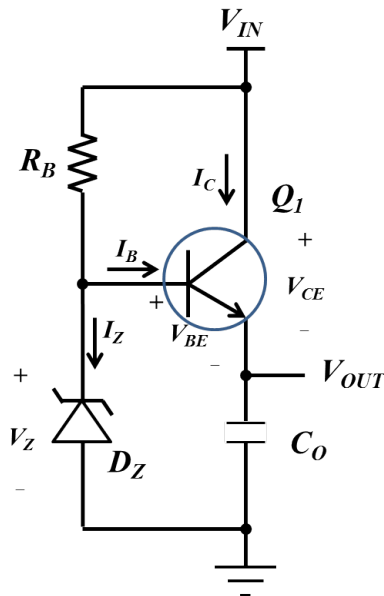


Figure 1. A simple series voltage regulator.

There are two design challenges related to the circuit shown in Figure 1. The first challenge is to regulate output voltage, and the second challenge is to survive a short-circuit event. In this post, I will discuss how to design a robust linear regulator with discrete components.

Here is an example used to power a microcontroller:

- Input range: 8.4V to 12.6V.
- Output range: 1.71V to 3.7V.
- Maximum load current:  $I_{O\_max} = 20\text{mA}$ .

## Bipolar NPN Transistor Selection

The NPN bipolar transistor,  $Q_1$ , is the most important component. I selected this device first. The transistor should meet the following requirements:

- The collector-to-emitter and base-to-emitter breakdown voltage should be higher than the maximum input voltage,  $V_{in\_max}$ .
- The maximum allowable collector current should be greater than the maximum load current,  $I_{O\_max}$ .

Besides these two basic requirements, it is a good idea to use a component with alternative packages. When it comes to power dissipation, having this flexibility will ease the design process later. For this application, I selected a NPN transistor with alternative packages and different power ratings.

Here are the key characteristic of the NPN transistor I used.

With  $I_C = 50\text{mA}$ :

the DC current gain,  $h_{FE} = 60$ ;

the maximum collector-emitter saturation voltage  $V_{CEsat} = 300\text{mV}$ ;

the maximum base-emitter saturation voltage  $V_{BEsat} = 950\text{mV}$ .

### Zener Diode, Dz Selection

The output voltage is the reverse zener voltage,  $V_Z$ , subtracting the transistor base-to-emitter voltage,  $V_{BE}$ . Thus, the minimum reverse zener voltage meets the following requirement ([Equation 1](#)):

$$V_{z\_min} \geq V_{o\_min} + V_{BE\_max} \quad (1)$$

With  $V_{o\_min} = 1.71\text{V}$  and  $V_{BE\_max} = 0.95\text{V}$ ,  $V_{z\_min}$  should be greater than 2.65V.

For this application, I used a test condition of  $I_{ZT} = 1\text{mA}$  and selected a zener diode with the following characteristics:

With reverse current of  $I_{ZT} = 1\text{mA}$ , the minimum reverse voltage,  $V_{Z\_min} = 2.7\text{V}$ .

With reverse current of  $I_{ZT} = 5\text{mA}$ , the maximum reverse voltage,  $V_{Z\_max} = 3.8\text{V}$ .

### Base Pull-up Resistor, $R_B$

The resistor,  $R_B$ , provides current for both the zener diode and transistor base. It should provide sufficient current over the operating conditions. The zener diode reverse current,  $I_Z$ , should be greater than 1mA, as I discussed in the “zener diode, Dz selection” section. [Equation 2](#) estimates the maximum base current required for operation:

$$I_{B\_max} = \frac{I_{O\_max}}{h_{fe\_min}} \quad (2)$$

where  $h_{fe\_min} = 60$ . Thus,  $I_{B\_max} \approx 0.333\text{mA}$ .

[Equation 3](#) calculates the value of  $R_B$ . I used a resistor with 1% tolerance.

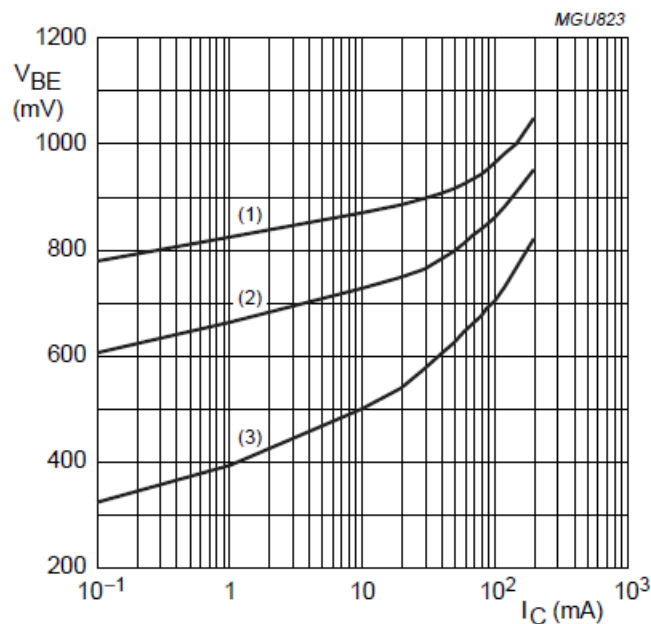
$$R_B \leq \frac{V_{in\_min} - V_{O\_min} - V_{BE\_max}}{(I_{B\_max} + I_{ZT}) \times (1 + Tol.)} \quad (3)$$

Thus,  $R_B$  should be less than 4.26k $\Omega$ . I used a resistor with a standard 4.22k $\Omega$  value.

Adding a dummy load resistor for output regulation

Output voltage is at its maximum when the load current is zero. With  $1\text{mA} \leq I_{ZT} \leq 5\text{mA}$ , the maximum  $V_Z$  is 3.8.  $V_{BE(on)}$  should be greater than 0.1V so that the output of the regulator meets the requirement. I added a dummy load resistor to draw a collector current for a no-load condition.

[Figure 2](#) shows  $V_{BE(on)}$  as a function of the collector current,  $I_C$ . With  $I_C = 0.1\text{mA}$ ,  $V_{BE(on)}$  is greater than 0.3V.



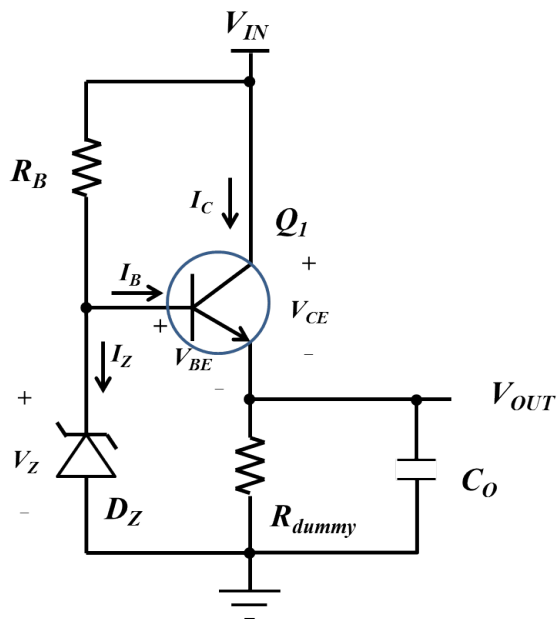
$V_{CE} = 1 \text{ V.}$   
 (1)  $T_{amb} = -55 \text{ }^{\circ}\text{C.}$   
 (2)  $T_{amb} = 25 \text{ }^{\circ}\text{C.}$   
 (3)  $T_{amb} = 150 \text{ }^{\circ}\text{C.}$

**Figure 2. Base-emitter on voltage versus collector current**

Equation 4 calculates the dummy resistor:

$$R_{dummy} \leq \frac{V_{o\_max}}{0.1mA} \quad (4)$$

I added a 36kΩ resistor to the circuit, as shown in Figure 3.



**Figure 3. Series voltage regulator with a dummy load resistor**

## Current Limiting for a Short-circuit Event

Shorting the output of the circuit shown in Figure 3 to ground will result in high collector current. A PSPICE simulation result shows that the collector current could be as high as 190mA; see Figure 4.

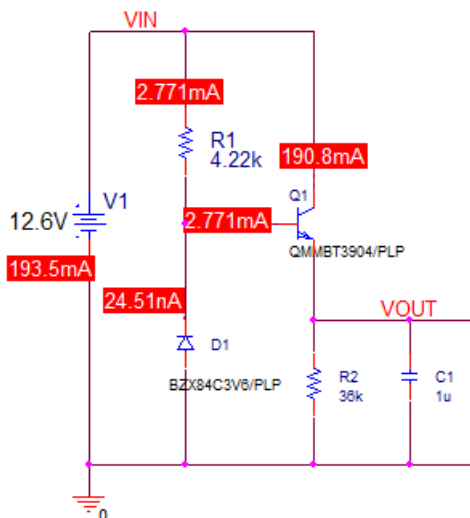


Figure 4. Short-circuit simulation result

The power dissipation on the transistor, Q<sub>1</sub>, is 2.4W. No package can handle this power dissipation.

To limit the short-circuit current, I added a resistor, R<sub>C</sub>, from V<sub>IN</sub> to the collector of the transistor, Q<sub>1</sub>, as shown in Figure 5.

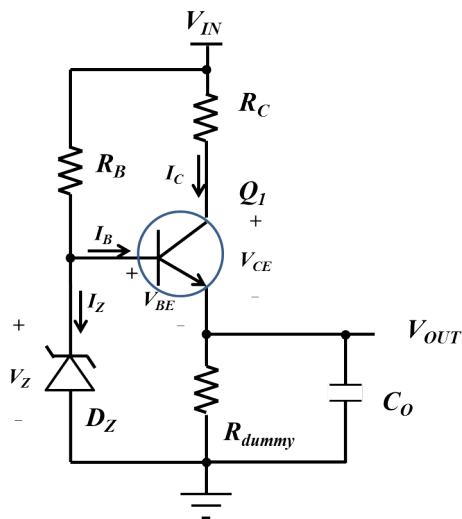


Figure 5. Series voltage regulator with a current-limiting resistor

The resistor, R<sub>C</sub>, will meet the output-regulation requirement and is capable of dissipating power during short-circuit events. I calculate the value of R<sub>C</sub>:

$$R_C \leq \frac{V_{in,min} - V_{o,min} - V_{CE,Test}}{I_{o,max} \times (1 + Tol.)} \quad (5)$$

V<sub>CE\_Test</sub> is the collector-emitter voltage used in Figure 1. I selected a 5% tolerance resistor for R<sub>C</sub>. Using Equation 5, R<sub>C</sub> should be less than 271Ω. With this estimated value, Equation 6 calculates the worst-case power dissipation on R<sub>C</sub> in a short-circuit event:

$$P_{RC\_SC} \approx \frac{(V_{in\_max} - V_{CEsat})^2}{R_C} \quad (6)$$

The power dissipation is about 0.56W. I selected a 1W, 270Ω power resistor. For applications with much higher short-circuit power dissipation on  $R_C$ , you can put multiple resistors in series to share the power.

### Component Stress Analysis

For the resistor,  $R_C$ , the worst-case power dissipation occurs in a short-circuit event with maximum input. Using Equation 6, the maximum power dissipation is 0.59W.

For the transistor,  $Q_1$ , the worst-case power dissipation is not during short-circuit event because of the current-limiting resistor,  $R_C$ . The power dissipation on  $Q_1$  during normal operation is a function of the collector current, as shown in Equation 7:

$$P_{Q1}(I_C) = (V_{IN} - V_o - R_C \times I_C) \times I_C \quad (7)$$

The worst case happens when:

$$V_{IN} = V_{IN\_max}$$

$$V_O = V_{O\_min}$$

$$I_C = (V_{IN\_max} - V_{O\_min}) / (2 \times R_C)$$

Thus, the maximum power dissipation on  $Q_1$  is  $(V_{IN\_max} - V_{O\_min})^2 / (4 \times R_C)$ . For this example, it is 110mW. I selected a small-outline-transistor, SOT23 package rated for 350mW.

For the maximum power dissipation on  $R_B$ , the worst case occurs during a short-circuit event with maximum input. The voltage across  $R_B$  is the input voltage subtracting the  $V_{BE(sat)}$ . The maximum power dissipation is estimated as 38mW.

In this post, I described the design guidelines for a robust, low-cost linear regulator with discrete components. This design process proves that integrated linear regulator from Texas Instruments provides much better output regulation and complete protections against over-voltage, short-circuit and over temperature.

### Additional Resources

- Read more Power Tips.
- View [Power Tips videos: https://training.ti.com/power-tips-training-series](https://training.ti.com/power-tips-training-series)
- Watch this [overview of NPN voltage regulators](#)

## IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#) or other applicable terms available either on [ti.com](#) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
Copyright © 2023, Texas Instruments Incorporated