AN59
Designing with Shunt Regulators - Series regulation

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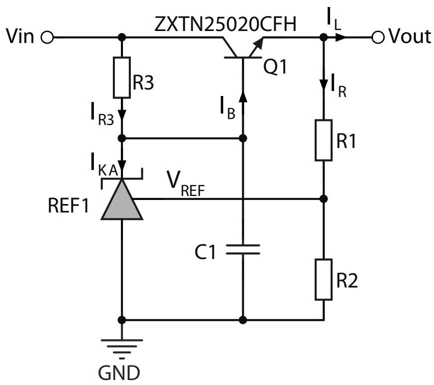
Introduction

Series regulators are versatile means of supplying power to many types of electronic circuits. Although both fixed and adjustable regulators are readily available off the shelf at competitive prices, there are instances when it may be desirable or necessary to design a discrete solution.

Such reasons might be due to requirement for a more accurate source than is commercially available - i.e. a precision regulator. These might be for instrumentation, calibration or environmental reasons. Low noise or level of required power might be other possible reasons for seeking a discrete solution.

The Zetex precision references can make implementation of these discrete solutions relatively simple. This document details the design considerations of the series regulator.

Basic Series Regulator



$$V_{OUT} = V_{REF}\left(1 + \frac{R1}{R2}\right)$$

$$R3 = \frac{V_{IN(\min)} - (V_{OUT} + V_{BE(\max)})}{I_{R3}}$$

$$\left(I_{B(\max)} + I_{KA(\min)}\right) \le I_{R3} \le I_{KA(\max)}$$

Figure 1 Basic series regulator using a reference

A series regulator has the advantage that the series element (Q1) has a different voltage across it from that across the load. This voltage can be arranged to be very low in comparison leading to a much lower power dissipation in the series element, Q1, than is being delivered to the load. In addition, There is little or no power dissipation in Q1 if there is no load (i.e. when IL = 0) other than the very small current due to IR. These are the reasons why it is a better method for medium/high power applications than the shunt regulator alone.

It is an irony and a practical benefit that the most important basic building block of a series regulator is a shunt regulator which can be readily identified in Figure 1. The series regulator is, at most, only as good as the quality of this shunt regulator which, in its crudest form, could be a zener diode. The function of the shunt regulator is not to power the load but to drive the transistor which powers the load. As long as Q1 is suitably sized, this simple circuit can be configured to supply very high power and current running into several 10's of amperes and hundreds of Watts.

Q1 could be a single device as shown or it could be a Darlington pair or even several transistors in parallel as the need may be.

Accuracy

The accuracy of the circuit is affected only by three components: the tolerance of the reference and that of resistors R1 and R2. See Appendix in AN57 for further information on this.

Calculated Example 1

Requirement

Supply Voltage: 12V to 15V
Output voltage: 10V ±1%
Load current: 100mA

Assume the use of TLV431.

Discussion

The ZXTN25020CFH transistor is used in this example because it offers a high forward gain (180 - 500) and a fairly high power handling capability (1.25W) for a device in a SOT23 package.

The equations for determining R1, R2 and accuracy are the same as in all reference applications. The objective here is to determine R1, R2 and R3 and check that the transistor Q1 can handle any resultant power dissipation.

Solution

R1 and R2 are chosen to be high enough in value that significant power is not wasted. On the other hand they need to be low enough that regulation accuracy and stability are achieved. Either R1 or R2 can be arbitrarily fixed and the other calculated from

$$V_{OUT} = V_{REF}\left(1 + \frac{R1}{R2}\right) \qquad \textbf{Equation 1}$$

AN57 showed the benefit of choosing a value of R1 in the region of 100kohm. Assume R1 is 100k and rearrange Equation 1 to obtain

$$R2 = \frac{R1}{\left(\frac{V_{OUT}}{V_{REF}} - 1\right)}$$

$$R2 = \frac{100k}{\left(\frac{10}{1.24} - 1\right)}$$

= 14.15k

Or R2 = 14.2k to the nearest E192 value and within 0.35%.

Determine maximum required base current, $I_{B(max)}$

$$I_{B(\max)} = \frac{I_{OUT(\max)}}{h_{FE(\min)} + 1}$$

$$= \frac{100mA}{181}$$

Hence, $I_{B(max)} = 552.5\mu A$

This is the maximum base current required by the transistor. R3 needs to be able to supply this plus, at least, the minimum cathode current for the TLV431 which is 100µA.

Therefore, $I_{R3(min)} = 652.5\mu A$

$$R3 = \frac{V_{IN(min)} - (V_{OUT} + V_{BE(max)})}{I_{R3(min)}}$$

$$R3 = \frac{12 - (10 + 0.9)}{652.5\mu A}$$

$= 1.68\ k\Omega$

Or $1.6\ k\Omega$ to the nearest lower E24 value.

Off-load and at maximum input, all of I_{R3} will flow into the TLV431 and it is necessary to check that this current will not be excessive.

Hence,

$$I_{R3(max)} = \frac{V_{IN(max)} - (V_{OUT} + V_{BE(min)})}{R3}$$

$$\frac{15 - 10.6}{1600}$$

$= 2.75mA$ less than 15mA as required.

The last thing to check is that the transistor is suitably power-rated for this application.

Hence,

$$P_{Q1(max)} = (V_{IN(max)} - V_{OUT}) \cdot \left(\frac{h_{FE(max)}}{h_{FE(max)} + 1}\right) I_{OUT}$$

$$= (15 - 10) \cdot 0.998 \cdot 0.1$$

$= 0.5W$ This is comfortably within the capability of the ZXTN25020CFH when suitably mounted.

Accuracy

It is necessary to determine the required component tolerances for meeting the specified accuracy. Since the design calls for an accuracy of ±1%, it follows that the TLV431 used must be the 0.5% tolerance part. The resistors' tolerance can then be calculated as follows (see AN57 Shunt Regulators for more information):

First determine α_{RD}

$$\alpha_{RD} = \left(\frac{R1}{R1 + R2}\right)(\alpha_{R1} - \alpha_{R2})$$

This is the error caused by using preferred resistors as opposed to calculated values.

$$\alpha_{RD} = \left(\frac{100k}{100k + 14.15k}\right)(0 - 0.35)$$

$$\alpha_{RD} = -0.31\%$$

R1, R2 tolerance,

$$\alpha_R = \pm\left[\left(\frac{\alpha_{VOUT} - (\alpha_{TLV431} + \alpha_{RD})}{2}\right)\left(\frac{R1 + R2}{R1}\right)\right]$$

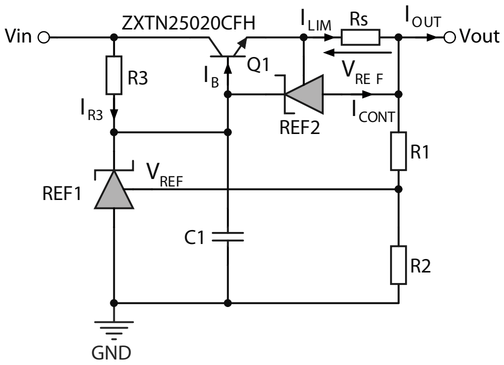
$$\alpha_R = \pm\left[\left(\frac{1 - (0.5 - 0.31)}{2}\right)\left(\frac{114.2}{100}\right)\right]$$

$$\alpha_R = \pm 0.463\%$$

Summary

Using a TLV431B, R1 = 100k, R2 = 14.2k (both 0.463% or better) and R3 = 1.6k will satisfy the requirement.

Series Regulator with Current Limit



$$V_{OUT} = V_{REF}\left(1 + \frac{R1}{R2}\right)$$

$$R3 = \frac{V_{IN} - (V_{OUT} + V_{REF} + V_{BE})}{I_{R3}}$$

$$\left(I_{B(\max)} + I_{KA(\min)}\right) \le I_{R3} \le I_{KA(\max)}$$

$$R_S = \frac{V_{REF}}{I_{LIM}}$$

Figure 2 Series regulator with current limit

The circuit in Figure 1 has no current limit. If a short circuit were to be applied to the output, the resultant current, ISC, that would flow can potentially be

$$I_{SC} = (h_{FE(\max)} + 1)\left(\frac{V_{IN(\max)} - V_{BE)}}{R3}\right) \qquad = (501)\left(\frac{15 - 0.9}{1600}\right)$$

I_{SC} = 4.4A

The ZXTN25020CFH, with its IC(cont) rating of 4.5A could handle this current. A much more serious issue is that all of the supply voltage now appears across Q1 at the same time. At 15V this amounts to a power dissipation of 66W. According to the Pulse Power Dissipation chart in the ZXTN25020CFH datasheet, the transistor will fail in less than 0.3ms if subjected to this level of power.

Figure 2 adds current limit to the series regulator in Figure 1 using a second reference (REF2), also a TLV431. For currents below the limit, the circuit works normally supplying the required load current at the design voltage. However, should attempts be made to exceed the design current set by REF2, the device begins to shunt current away from the base of Q1. This begins to reduce the output voltage and thus ensuring that the output current is clamped at the design value. Subject only to Q1's ability to withstand the resulting power dissipation, the circuit can withstand either a brief or indefinite short circuit.

Calculated Example 2

Requirement

Add a 105mA ±5% current limit to Calculated Example 1 (Figure 1 Basic series regulator).

Solution

$$R_S = \frac{V_{REF}}{I_{LIM}}$$

$$= \frac{1.24}{0.105}$$

= 11.81

or R_S = 11.8 Ω To nearest E48 value.

Using a 1% device (TLV431A), an R_S value of 11.8Ω 1% makes the worst case cumulative error 2%, within ±5% as required.

Determination of actual short circuit current

When the current limit circuit is operative, the output current consists of two components as shown below. I_{LIM} remains constant, I_{CONT} varies continuously with the level of overload until reaching a maximum at full short circuit i.e. when $V_{OUT} = 0$.

Hence

$$I_{OUT(\max)} = I_{LIM} + I_{CONT}$$

$$= I_{LIM} + \left(\frac{V_{IN(\max)} - (V_{REF} + V_{BE})}{R3} - \frac{I_{LIM}}{h_{FE} + 1}\right)$$

$$= I_{LIM}\left(\frac{h_{FE}}{h_{FE} + 1}\right) + \frac{V_{IN(\max)} - (V_{REF} + V_{BE})}{R3}$$

$$\approx I_{LIM} + \frac{V_{IN(\max)} - (V_{REF} + V_{BE})}{R3}$$ since $h_{FE} >> 1$

Therefore,

$$I_{OUT(\max)} = \frac{1.24}{11.8} + \frac{15 - (1.24 + 0.6)}{1600}$$

$I_{OUT(max)}$ = 113.3mA

This represents the maximum short circuit current, it is not the current seen by transistor Q1 which is given by

$$I_C = I_{LIM}\left(\frac{h_{FE}}{1 + h_{FE}}\right)$$

$$\approx I_{LIM}$$ if $h_{FE} >> 1$

Therefore I_C = 105mA

This means that a direct short circuit would not immediately result in a failure. It is still however necessary to estimate how long the circuit could withstand such an overload condition for as follows.

Overload duration

With a short circuit, the current will be limited to a maximum of 107mA (105 +2%). Worst case voltage across Q1 will be 13.76V (i.e. 15V - 1.24V). Therefore, Q1's dissipation will be 1.47W. Referring to the Pulse Power Dissipation chart in the ZXTN25020CFH datasheet, it can be seen that Q1 will withstand this condition for between 10s and 100s. This is if there is a direct short circuit of the output voltage. If there is only a partial overload, the situation will be far less severe.

There are a number of steps that can be taken if an indefinite short circuit handling capability is required. The simplest action would be to use a slightly bigger transistor for Q1. For example, the ZXTN2005G is a transistor in a SOT223 package and will dissipate up to 3W continuously when suitably mounted.

Another method that could be used is to apply a re-entrant or "fold-back" current limiting rather than the simple current limiting above. This is a method which adjusts the over-load current limit according to the value of the output voltage such that, by the time the output voltage drops to zero - i.e. a short circuit, the current limit has dropped to a very small value, typically 5% or less of the full load current. This is a more complex solution and is outside the scope of this document.

Conclusion

Precision series regulators can be implemented using references. These allow the user to have more control of both the qualitative (e.g. accuracy) and quantitative (e.g. output voltage, current limit or power delivery) to suit the application.

Recommended further reading

AN58 - Designing with Shunt Regulators - *Shunt Regulation*

AN60 - Designing with Shunt Regulators - *Fixed Regulators and Opto-Isolation*

AN61 - Designing with Shunt Regulators - *Extending the operating voltage range*

AN62 - Designing with Shunt Regulators - *Other Applications*

AN63 - Designing with Shunt Regulators - *ZXRE060 Low Voltage Regulator*

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