AN58

Designing with References - Shunt regulation

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Introduction

This application note introduces shunt regulators, sometimes called "reference diodes", "3-terminal voltage references", or "adjustable voltage references". Using worked examples we introduce some applications of adjustable (3-terminal) shunt regulators.

Diodes' range of three-terminal adjustable shunt regulators offer temperature stabilised reference voltage values ranging from 0.6V to 2.5V with an initial tolerance of 0.5% or 1% and maximum current sinking capability from 18mA to 200mA. Maximum operating voltage ranges from 18V to 36V.

Adjustable references can be used as replacements for zener diodes in many applications that require an improved regulation. Also they can also be used in conjunction with other types of voltage regulators to improve the initial accuracy and regulation. This is discussed elsewhere particularly in the references provided towards the end of this document.

The information presented in this Applications Note shows typical basic use of references with calculated examples.

What are they?

A reference in its basic form is a two terminal device that functionally behaves like a zener diode. The same circuit symbol is used for both of them as shown in Figure 1. A reference is therefore a shunt regulator and is quite often referred to as such. Note the polarity and direction of current flow.

The primary difference between a zener diode and a reference lies in the accuracy of the two devices. Relative to a zener diode, a reference is a precision component. It is more accurate with a wider dynamic range of operation and better figures of merit all round. A reference can, for example, work over a current range of 500µA to 50mA (a dynamic range of 100:1) with little or no practical change in its key properties. This can never be possible with a zener diode which may typically work with a dynamic range of 2:1 or less and still perform worse than a reference.

The reference is able to do this because, internally, it is in fact an integrated circuit containing amplifiers and temperature/stability compensating elements. A zener on the other hand is simply a specially fabricated p-n junction diode.

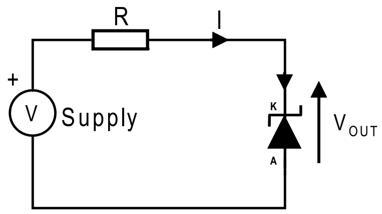


Figure 1 - Shunt Regulator using a zener diode or a 2-terminal reference diode

Adjustable or 3-terminal references

Whereas the standard reference comes in a narrow range of fixed voltages with two terminals, the adjustable kind has a third terminal which allows the user to set any output voltage in a prescribed range. It is often referred to as a "three-terminal reference". The third pin is interchangeably labelled "Ref" (reference pin), "Adj" (adjustment pin) or "FB" (feedback pin). The usual circuit symbol for an adjustable reference is shown in Figure 2 below.

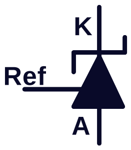
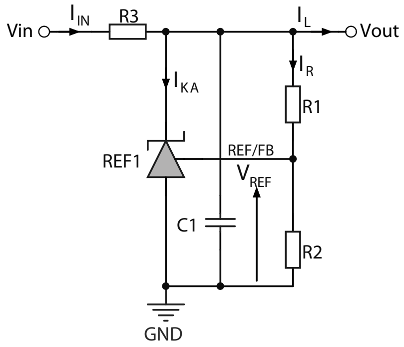


Figure 2 - Adjustable or 3-terminal reference

Applications

Basic Shunt Regulator



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

$$R3 = \frac{V_{IN} - V_{OUT}}{I_{IN}}$$

$$\Delta I_{L(\max)} \le \left(I_{KA(\max)} - I_{KA(\min)}\right)$$

Figure 3 Basic shunt regulator

The basic shunt regulator circuit using a 2-terminal device has been shown in Figure 1. The low dynamic resistance of the diode establishes a voltage across the resistor which determines the resistor current. The same circuit function using a 3-terminal reference is shown in Figure 3 above. In response to changes in V_{in} or the load current, I_L, REF1 will adjust how much current it sinks or "shunts" to maintain a voltage equal to V_{REF} across its feedback (FB) or reference (REF) pin. It will be noticed that the input current, I_{IN}, is the sum of three components, I_{KA}, I_L and I_R. Usually R1 and R2 are chosen such that I_R is much less than I_{IN} to maximise the current that is available to the load.

REF1 has a minimum bias current requirement, $I_{KA(min)}$, below which it is not able to operate. This is analogous to the "knee" current of a zener diode. Also it has a maximum current sink capability, $I_{KA(max)}$, beyond which the device will become unreliable or it will fail. These two parameters define the limit of use of the reference regulator within its maximum programmable voltage such that, at all times,

$$\Delta I_{L(\max)} \le \left(I_{KA(\max)} - I_{KA(\min)}\right)$$

The equation above for V_{OUT} is accurate for most practical purposes. However it does not include the effect of the input current at the REF pin of the reference device. A more accurate expression is:

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

where I_{REF} is the REF pin input current. I_{REF} is typically 40nA or less for the TLV431. For example, if R1=100kohm, V_{OUT} is 4mV greater than that given by the simple formula. For the TLV431, this resistor value is a good choice because it also gives very low power dissipation in the feedback network.

Calculated Example 1

Requirement

Supply Voltage:	15V to 20V
Output voltage:	10V ±1%
Load current:	5mA

Assume the use of TLV43[1] .

Discussion

The device needs some overhead current whilst delivering 5mA. The TLV431 can work with as little as 100µA shunt current.

Let's assume R1 will be approximately 100kΩ as discussed above. The voltage divider ratio is 10V/1.24V or roughly 8 to 1. Then R2 will be of the order of 10 or 12kΩ. Choosing R2 = 10k, this makes the current, I_R, equal to 1.24V/10kΩ = 124µA. The minimum current requirement of the TLV431 is $I_{KA(min)}$ = 100µA. Therefore, allowance for a minimum overhead current of 224µA (i.e. $I_{KA(min)} + I_R$) must be made. Allowing for a safety margin, this might be rounded up to 250µA. More margin could be allowed but this could result in unnecessary wasted power which would especially be expensive for battery powered applications.

This means the circuit, or more specifically, R3, needs to supply 5.25mA under worst case input condition which is 15V.

Solution

Therefore,

$$R3 = \frac{V_{IN(\min)} - V_{OUT}}{I_{IN}} = \frac{15 - 10}{0.00525} = 952.38\Omega$$

R3 = 953Ω to the nearest E48 value.

Check that the maximum current handling capability of the TLV431 is not exceeded:

Maximum current

$$I_{\max} = \frac{V_{IN(\max)} - V_{OUT}}{R3} = \frac{20 - 10}{953}$$

I_{max} = 10.5mA - This is less than 15mA as required.

Lastly, although this could have been computed first, R1 is determined thus,

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

Re-arrange to obtain

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

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

$$= 70.64k$$

Or R1 = 70.6k to the nearest E192 value and within 0.057%.

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[1] The same principles apply for all of Diodes' shunt regulators.

Component Tolerances

Given the expression in Equation 1, the accuracy, α_{vout}, of the output voltage can be expressed in the reduced form as,

Equation 2

$$\alpha_{VOUT} = \pm\left(\alpha_{TLV431} + 2\cdot\alpha_{R}\left(\frac{R1}{R1+R2}\right)\right)$$

(see Appendix for proof)

where α_{TLV431} = Manufacturing tolerance of TLV431

α_{R} = Manufacturing tolerance of resistors R1 and R2 (different values but equal fractional tolerance)

This expression applies provided both R1 and R2 are exact values as calculated. If preferred values, other than calculated ones, have to be used the error is given by

Equation 3

$$\alpha_{VOUT} = \pm\left[\alpha_{TLV431} + \alpha_{RD} + 2\cdot\alpha_{RP}\left(\frac{R1_C}{R1_C + R2_C}\right)\right]$$

(see Appendix for proof)

where, as before, α_{TLV431} = Manufacturing tolerance of TLV431

α_{RP} = Manufacturing tolerance of preferred resistors $R1_P$ and $R2_P$ (see Appendix for more explanation)
$R1_C$, $R2_C$ are the Calculated values of R1 and R2 respectively.

And the new term, α_{RD} = Weighted deviation of resistors R1 and R2 from their calculated values given by,

$$\alpha_{RD} = \left(\frac{R1_C}{R1_C + R2_C}\right)(\alpha_{R1D} - \alpha_{R2D})$$

where α_{R1} and α_{R2} are fractional deviations of R1 and R2 from their calculated values respectively. Both are sign critical.

Equation 4

Since the problem requires an accuracy of ±1%, only the TLV431B (0.5% tolerance) can be used. This then leaves 0.5% to be shared by the two resistors and any deviation from their standard values. Also because the calculated R1 is not a preferred value, Equation 3 rather than Equation 2 has to be used.

Hence from Equation 4

$$\alpha_{RD} = \left(\frac{70.64k}{70.64k + 10k}\right)(-0.057 - 0)$$

$$\alpha_{RD} = -0.05\%$$

Transposing Equation 3

$$\alpha_{RP} = \pm\left[\left(\frac{\alpha_{VOUT} - (\alpha_{TLV431} + \alpha_{RD})}{2}\right)\left(\frac{R1_C + R2_C}{R1_C}\right)\right]$$

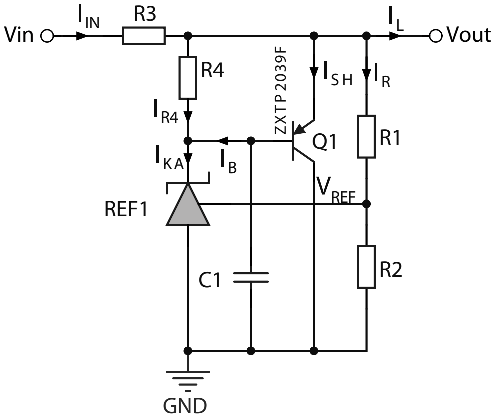
$$= \pm\left[\left(\frac{1-(0.5-0.05)}{2}\right)\left(\frac{70.64+10}{70.64}\right)\right]$$

$$\alpha_{RP} = \pm 0.31\%$$

Summary

Using a TLV431B, R1 = 70.6k, R2 = 10k (both 0.31% or better) and R3 = 953Ω will satisfy the requirement.

Current-boosted Shunt Regulator



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

$$R3 = \frac{V_{IN} - V_{OUT}}{I_{IN}}$$

$$I_{IN} = I_{R4} + I_{SH} + I_L + I_R$$

Figure 4 - High current shunt regulator

It may at times be required to shunt-regulate more current than a reference device is capable of providing. Figure 4 shows how this can be done using a transistor Q1 to provide current amplification.

Calculated Example 2

Requirement

Supply Voltage:	15V to 20V
Output voltage:	10V ±1%
Load current:	20mA

Assume the use of TLV431.

Discussion

This problem is similar to Calculated Example 1 above except that more load current is required. The values calculated for R1 and R2 are still valid. However, R3 will need to be recalculated. I_R remains the same but I_{KA} now consists of two components (I_{R4} + I_B) whilst there is a new term, I_{SH}. The overhead current can remain the same at 0.25mA making the total current through R3 20.25mA.

Q1 is under the control of the reference and it is important that the reference can turn it fully off if necessary. R4 is chosen to enable this. As a minimum requirement therefore, R4 will be chosen to ensure that the voltage drop across it at $I_{KA(min)}$ is insufficient to turn on Q1. This will be the case if V_{BE} at $I_{KA(min)}$ is kept to no more than 0.2V. In reality it would make more sense to allow the reference to supply as much of the shunt current as possible before bringing Q1 into service as this will result in the least strain on Q1. It will also mean that the reference would not have problem turning Q1 off to maximise power delivery to load.

Solution

$$R3 = \frac{V_{IN(\min)} - V_{OUT}}{I_{IN}} = \frac{15-10}{0.02025}$$

$$= 246.9\Omega$$

$$R3 = 240\Omega$$ to the nearest lower E24 value.

To determine R4, we need to know at what nominal current Q1 will be brought into service. Let this nominal hand-over current be I_{HC}.

$I_{B(\max)} < I_{HC} < 20mA$

Let I_{HC} = 10mA. Therefore,

$$R4 = \frac{V_{BE}}{I_{HC}}$$

$$= \frac{0.6}{10mA}$$

$$= 60\Omega$$

Hence, R4 = 62Ω to the nearest E24 value.

At maximum voltage however,

Maximum current

$$I_{IN(\max)} = \frac{V_{IN(\max)} - V_{OUT}}{R3} = \frac{20-10}{240}$$

$$= 41.67\text{mA}$$

This figure shows the wisdom of allowing the TLV431 to supply as much of the load current as possible before bringing Q1 into service. Had R4 been selected so that REF1 only supplies enough current for its own bias (i.e. 100µA), Q1 would be required to carry 41.57mA. With an output voltage of 10V, this would result in a power dissipation of 415.7mW in Q1 which is too much for the specified device to handle. As it is, with REF1 carrying 10mA, Q1 only needs to carry the remaining 31.67A. This would result in a power dissipation of 316.7mW which is more within the capability of Q1[2].

Determination of I_B

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

$$= \frac{31.67mA}{101}$$

$$I_B = 313.6\mu A$$

This represents a very small contribution to the 10mA flowing through R4 making the total current, I_{KA} = 10.31mA.

Accuracy

The same accuracy considerations as in applies here. Neither R3, R4 nor Q1 have any bearing on accuracy.

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[2] The ZXTP2039F is a SOT23 transistor with a VCEO rating of -60V, an IC of -1A and can dissipate up to 350mW when suitably mounted. Refer to datasheet ZXTP2039F.

Conclusion

The above examples show basic considerations for use of references and amply demonstrate how easy it is to design with these versatile components.

Recommended further reading

AN59 - Designing with Shunt Regulators – *Series 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*

Appendix - Calculating output error due to components' preferred values and tolerances

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

Transfer function

$$\alpha_{VOUT} = \frac{\delta V_{OUT}}{V_{OUT}}$$

- definition of fractional tolerance

$$\delta V_{OUT} = \frac{\partial V_{OUT}}{\partial V_{REF}}\cdot\delta V_{REF} + \frac{\partial V_{OUT}}{\partial R1}\cdot\delta R1 + \frac{\partial V_{OUT}}{\partial R2}\cdot\delta R2$$

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

Therefore,

$$\alpha_{VOUT} = \frac{\delta V_{OUT}}{V_{OUT}} = \frac{\delta V_{REF}}{V_{REF}} + \left(\frac{R1}{R1+R2}\right)\left(\frac{\delta R1}{R1}-\frac{\delta R2}{R2}\right)$$

Equation 5

Or

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

Equation 6

It can be observed that the result consists of two terms namely the fractional tolerance of the reference itself and the manufacturing fractional tolerance of the two resistors, R1 and R2. It is entirely logical that these resistors will be of identical types of equal tolerance. Therefore, their worst case would be obtained when one resistor's tolerance is to one extreme and the other to the opposite extreme. This would result in their tolerances being an integer multiple with the appropriate sign as the case may be

Therefore, Equation 6 becomes

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

Equation 7

where α_R
= tolerance of resistors

This represents the worst case error using the calculated resistor values. Very often, the calculated value would not be exactly the same as a preferred value, resulting in additional deviation error. This deviation of actual resistor from calculated value needs to be accounted for which means Equation 6 needs to be modified. This is done by defining another error term representing the combined deviation of both resistors from their calculated values such that the overall error would then be

$$\alpha_{VOUT} = \pm\left[\alpha_{VREF} + \alpha_{\underline{\underline{RD}}} + \alpha_{\underline{\underline{RPE}}}\right]$$

where α_{RD} = error due to preferred value and

Equation 8

α_{RPE} = error due to tolerance of the preferred value resistor

The task then is determining α_{RD} and α_{RPE} as follows.

Consider the second term in the RHS of Equation 5. Each δR can be assumed to consist of two components namely,

1. An error due to choosing a preferred resistor value different from the calculated one, and
2. The basic tolerance of the preferred resistor itself.

Let Rn_C = Calculated value of Rn, and
Rn_P = Preferred value of Rn.

Let $\alpha_{RnD} = \frac{R_{nP} - R_{nC}}{R_{nC}} = \frac{\delta R_{nC}}{R_{nC}}$ =Error due to changing from Rn_C to Rn_P,

and

α_{RnP} = Tolerance of Rn_P.

Thus, from Equation 5,

$$\left(\frac{\delta R1}{R1}-\frac{\delta R2}{R2}\right) \equiv \left(\frac{\delta R1_C + \alpha_{R1P}\cdot R1_P}{R1_C}\right)-\left(\frac{\delta R2_C + \alpha_{R2P}\cdot R2_P}{R2_C}\right)$$

Equation 9

$$\left(\frac{\delta R1}{R1}-\frac{\delta R2}{R2}\right) = \left(\frac{\delta R1_C}{R1_C} + \frac{\alpha_{R1P}\cdot R1_P}{R1_C}\right)-\left(\frac{\delta R2_C}{R2_C} + \frac{\alpha_{R2P}\cdot R2_P}{R2_C}\right)$$

Equation 10

Substituting Equation 10 into Equation 5 gives

$$\alpha_{VOUT} = \frac{\delta V_{REF}}{V_{REF}} + \left(\frac{R1_C}{R1_C + R2_C}\right)\left(\left(\frac{\delta R1_C}{R1_C} + \frac{\alpha_{R1P}\cdot R1_P}{R1_C}\right)-\left(\frac{\delta R2_C}{R2_C} + \frac{\alpha_{R2P}\cdot R2_P}{R2_C}\right)\right)$$

Re-arranging gives

$$\alpha_{VOUT} = \frac{\delta V_{REF}}{V_{REF}} + \left(\frac{R1_C}{R1_C + R2_C}\right)\left(\frac{\delta R1_C}{R1_C} - \frac{\delta R2_C}{R2_C}\right) + \left(\frac{R1_C}{R1_C + R2_C}\right)\left(\frac{\alpha_{R1P}\cdot R1_P}{R1_C} - \frac{\alpha_{R2P}\cdot R2_P}{R2_C}\right)$$

$$\alpha_{VOUT} = \alpha_{VREF} + \left(\frac{R1_C}{R1_C + R2_C}\right)(\alpha_{R1D} - \alpha_{R2D}) + \left(\frac{R1_C}{R1_C + R2_C}\right)\left(\frac{\alpha_{R1P}\cdot R1_P}{R1_C} - \frac{\alpha_{R2P}\cdot R2_P}{R2_C}\right)$$

Equation 11

Again assuming worst case conditions with $|\alpha_{R1P}| = |\alpha_{R2P}|$ (= α_{RP}) but opposite in sign,

$$\alpha_{VOUT} = \pm\left[\alpha_{VREF} + \left(\frac{R1_C}{R1_C + R2_C}\right)(\alpha_{R1D} - \alpha_{R2D}) + \left(\frac{\alpha_{RP}\cdot R1_C}{R1_C + R2_C}\right)\left(\frac{R1_P}{R1_C} + \frac{R2_P}{R2_C}\right)\right]$$

Equation 12

Check:

If both calculated R1 and R2 are the same as the preferred values, the expression reduces to

$$\alpha_{VOUT} = \pm\left[\alpha_{VREF} + 2\cdot\alpha_{RP}\left(\frac{R1_C}{R1_C + R2_C}\right)\right]$$

Same as Equation 7Equation 7

Also, comparing Equation 12 and Equation 8, it can be seen that,

$$\alpha_{RD} = \left(\frac{R1_C}{R1_C + R2_C}\right)(\alpha_{R1D} - \alpha_{R2D})$$

and,

$$\alpha_{RPE} = \left(\frac{\alpha_{RP}\cdot R1_C}{R1_C + R2_C}\right)\left(\frac{R1_P}{R1_C} + \frac{R2_P}{R2_C}\right)$$

As required.

In practice, one resistor (usually R2) is chosen by the user, effectively making its RC = RP, whilst the other is calculated. Also, if the remaining resistor's RP is very close to its RC, as is more likely than not, then is a valid assumption. Applying these facts, Equation 12 becomes,

Equation 13

$$\alpha_{VOUT} = \pm\left[\alpha_{VREF} + \alpha_{RD} + 2 \cdot \alpha_{RP}\left(\frac{R1_C}{R1_C + R2_C}\right)\right]$$

As required.

Summary

The cumulative error caused by variation in values of the component parts is given by Equation 12 which holds true under all conditions. However, in the special but realistic conditions given preceding it, Equation 13 produces the same result as Equation 12 with negligible difference.

The latter is simpler and easier to remember than the former and is the one used in Calculated Example 1.

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