AN61
Designing with References - Extending the operating voltage range

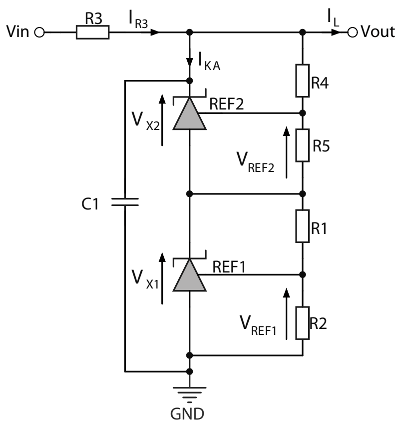
Peter Abiodun A. Bode, Snr. Applications Engineer, Diodes Zetex Ltd

Introduction

There may be times when it is required to shunt-regulate a higher voltage than the 3-terminal reference is designed for. This may be either as a stand alone shunt regulator or it may be as part of a series regulator arrangement.

The following circuits offer a number of suggestions on how this might be done.

Figure 1 simply cascades two references together. The output voltage is the sum of the two stages combined. It is worth noting that the output voltage and its accuracy is affected by both reference devices as well as the four resistors R1, R2, R4 and R5 meaning the errors are cumulative.



$$V_{OUT} = V_{X1} + V_{X2}$$

$$= V_{REF1}\left(1 + \frac{R1}{R2}\right) + V_{REF2}\left(1 + \frac{R4}{R5}\right)$$

Assuming $V_{REF1} = V_{REF2} = V_{REF}$

Then, $$V_{OUT} = V_{REF}\left(2 + \frac{R1}{R2} + \frac{R4}{R5}\right)$$

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

<u>Conditions</u>:

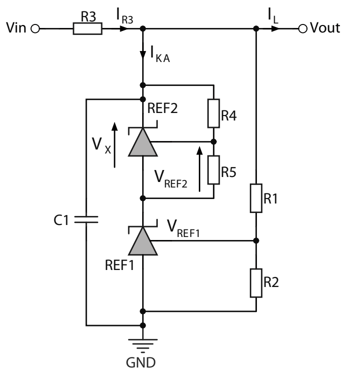
$$I_{KA(\min)} < I_{R3} \le I_{KA(\max)}$$

$$V_{REF} \le (V_{X1}, V_{X2}) \le V_{KA(\max)}$$

Figure 1 Higher voltage shunt regulator

This is not the case for either Figure 2 or Figure 3. In both cases, a device (another reference or a zener diode) is used to drop any excess voltage within the circuit whilst a reference, REF1, is primarily responsible for regulation.

The top device is "invisible" to the output voltage and is there purely as a protective device for the controlling reference to take up the excess voltage that would otherwise damage the bottom device. The output voltage and its accuracy are entirely determined by the controlling reference, R1 and R2.



$$V_{OUT} = V_{REF1}\left(1+\frac{R1}{R2}\right)$$

$$V_X = V_{REF2}\left(1+\frac{R4}{R5}\right)$$

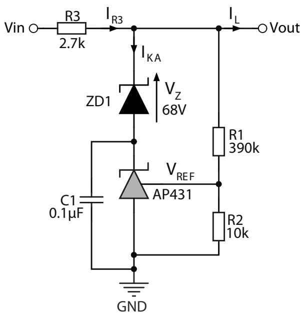
$$R3 = \frac{V_{IN} - V_{OUT}}{I_{R3}}$$

Conditions:

$$I_{KA(\min)} \le I_{R3} \le I_{KA(\max)}$$

$$(V_{KA(\min)} + V_X) \le V_{OUT} \le (V_{KA(\max)} + V_X)$$

Figure 2 Improved higher voltage shunt regulator



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

$$V_{Z(nom)} = V_{OUT} - V_{KA}$$

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

Conditions:

$$I_{KA(\min)} \le I_{R3} \le I_{KA(\max)}$$

$$(V_{KA(\min)} + V_Z) \le V_{OUT} \le (V_{KA(\max)} + V_Z)$$

Figure 3 Higher voltage shunt regulator with no limit

Calculated Example 1

Requirement

Supply Voltage: 60V to 75V
Output voltage: 50V
Load current: 5mA
Assume the use of AP431.

Discussion

The required voltage of 50V is higher than what could be handled by a single reference but within the capability of two references. The AP431 with its $V_{KA(max)}$ rating of 36V is ideal for this problem. It is assumed therefore that the 2-reference solution in Figure 2 will be used.

Solution

First, determine R1 assuming R2 = 10k.

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

$$= 10k\left(\frac{50}{2.495} - 1\right)$$

= 190.4k

Or R1 = <u>191k</u> to the nearest E192 value and within 0.32%.

Next determine I_{R3}.

This will be the required load current plus the minimum operating current of the AP431, $I_{KA(min)}$ which can be as much as 0.5mA.

Hence, I_{R3} = 5.5mA.

Next, determine R3 and V_X, R4 and R5. The optimum thing to do is to ensure that the circuit is able to supply the required current under worst case conditions and then check that all devices still work within their design parameters at the opposite extreme.

Worst case conditions are full load current and minimum input voltage.

Hence,

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

$$= \frac{10}{0.0055}$$

$$= 1.81k\Omega$$

R3 = 1.8k to the nearest lower value in E12.

It is best to ensure V_{OUT} is equidistributed across the two references.

Therefore, $V_X = V_{OUT}/2$
= 25V

Assuming R5 = 10k

$$R6 = R5\left(\frac{V_{OUT}}{V_{REF}} - 1\right)$$

$$= 10k\left(\frac{25}{2.495} - 1\right)$$

= 90.2k

Or R4 = 90.9k to the nearest E48 value.

Figure 4 below shows the circuit with all circuit values. The last exercise now is to verify that all will be well even at the opposite extreme of the worst conditions that were used to calculate these values.

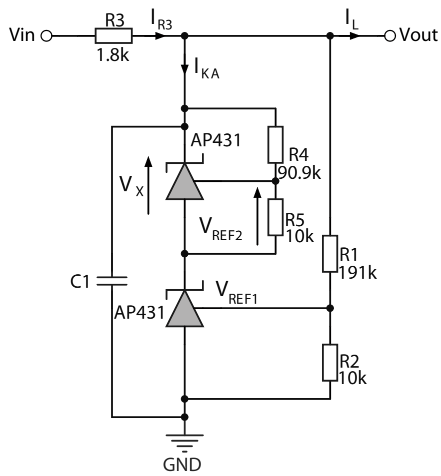


Figure 4 50V shunt regulator using two AP431s

The worst case conditions are full load current and minimum input voltage. The opposite extremes will be maximum input and no load. What would happen to all circuit elements under these conditions?

The output voltage will remain at 50V and equally distributed across the references but all of I_{R3} will now flow into them. However, I_{R3} is now $I_{R3(max)}$ which is given by

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

$$= \frac{25}{1800}$$

$$= 13.9mA$$

Since the AP431 can sink up to 200mA this is not a problem. However the power dissipation in each device will only be 25V x 13.9mA = 347.5mW. Therefore a suitable package to handle this power will have to be chosen.

The AP431 comes in several package options. These range from the SOT23 handling 400mW up to SOT89 handling 800mW. A SOT23 device might just be good enough for the above solution but this is at 25°C and will have to be derated for higher ambient temperatures. A bigger package may be needed.

Lastly the power rating of R3 needs to be decided.

Thus,

$$P_{R3(\max)} = \frac{(V_{IN(\max)} - V_{OUT})^2}{R3}$$

$$= \frac{25^2}{1800}$$

$$P_{R3(max)} = 347.2mW$$

To keep surface temperature rise to a minimum a resistor rated at least 0.5W should be used.

The circuit in Figure 4 was both bench tested and simulated and the graphs below show the results.

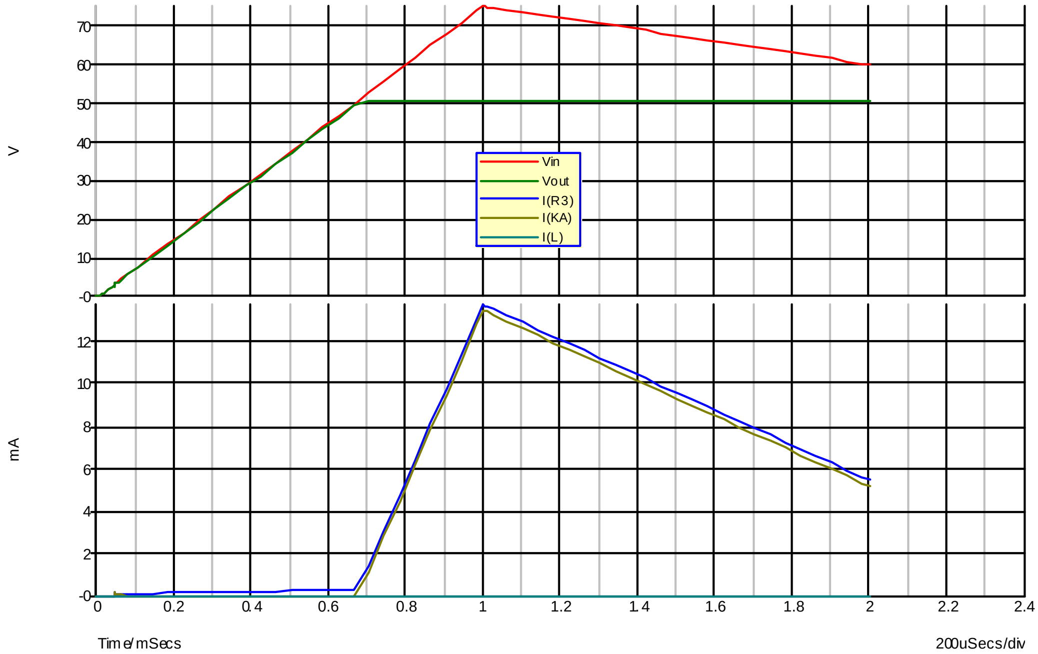


Figure 5 Two-reference circuit without a load

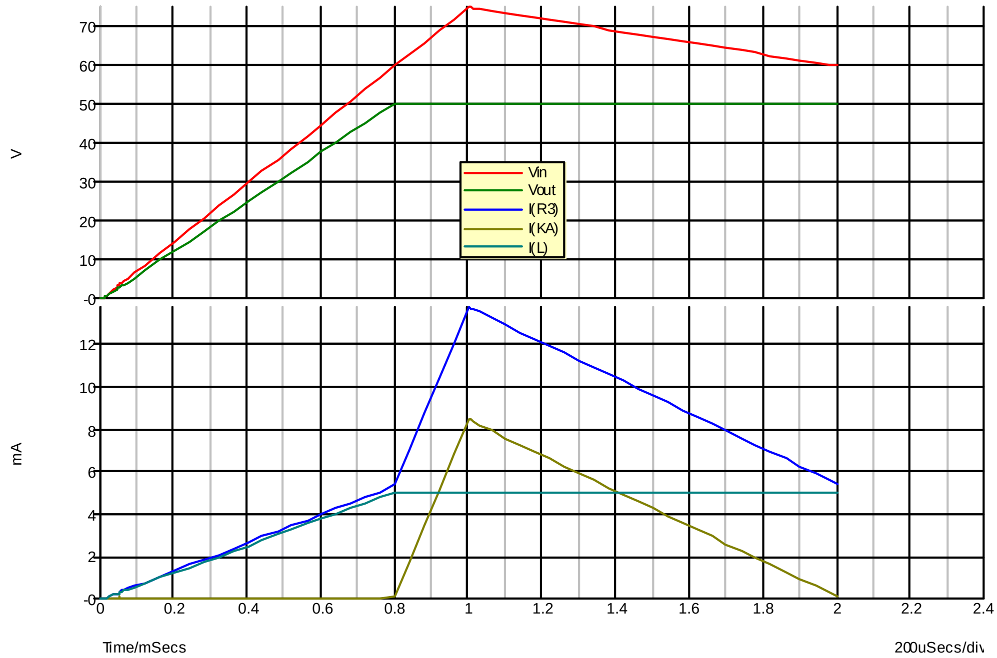


Figure 6 Two-reference circuit with a 10k load

Figure 5 shows the test without any load, hence all of the available current goes into the regulator chain. When loaded with a 10k resistor as shown in Figure 6, the load takes a constant current of 5mA regardless of the input voltage.

Calculated Example 2

Requirement

Supply Voltage: 115V to 135V
Output voltage: 100V
Load current: 5mA

Assume the use of AP431.

Discussion

The required voltage of 100V is higher than what even two AP431's could handle. Technically, three or more references could be cascade connected following the same principle in Figure 2. A better solution might be to replace the dropper reference with a zener diode as shown in Figure 3.

Solution

The design considerations are the same as for Calculated Example 1 except that it is not possible to have the output voltage equidistributed across the reference and zener diode which needs to necessarily carry the bulk of the voltage.

Hence, determine R1 assuming R2 = 10k.

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

$$= 10k\left(\frac{100}{2.495} - 1\right)$$

$$= 390.8k$$

Or $R1 = \underline{390k}$ to the nearest E12 value and within 0.21%.

Determine IR3.

$$I_{R3} = I_L + 0.5mA$$
$$= 5.5mA$$

Next, determine R3 and V_Z, R4 and R5.

Worst case conditions are full load current and minimum input voltage.

Hence,

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

$$= \frac{15}{0.0055}$$

$$= 2.73k\Omega$$

R3 = 2.7k to the nearest lower value in E12.

With a V_{OUT} of 100V and the need to keep V_{KA} within 36V, it is evident that V_Z can not be less than 64V. Therefore a V_{KA} value of 30V may be adopted for the design. This means V_Z will have to be 70V.

Like most electronic components, zener diodes are only available in certain preferred voltage values, usually from the E24 preferred values list. Therefore a search for the nearest preferred value to 70V needs to be carried out.

The two nearest values to 70V from the E24 table are 68V and 75V of which 68V is the nearer of the two. This will make V_{KA} 32V which is still within 36V.

$$V_Z = 68V$$

Figure 7 below shows the circuit with all circuit values.

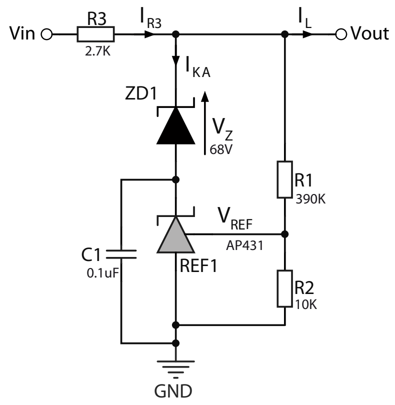


Figure 7 100V shunt regulator using one AP431 and a zener diode

High input worst case analysis

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

$$= \frac{135 - 100}{2700}$$

$$= 12.96\text{mA}$$

Less than 200mA as required.

Power ratings

Power in AP431:

$$P_{(AP431)} = V_{KA} \cdot I_{R3(\max)}$$

$$= 32 \times 0.013$$

$$P_{(AP431)} = 416\text{mW}$$

This is too much power for the SOT23, Therefore a bigger package will be required. Alternatively, the power could be reduced by reducing the voltage dropped by it.

Power in ZD1:

$$P_{(ZD1)} = V_Z \cdot I_{R3(\max)}$$

$$= 68 \times 0.013$$

$$P_{(ZD1)} = 884\text{mW}$$

A zener diode with a power rating of at least twice this is recommended.

Power in R3:

$$P_{(R3)} = V_{R3(\max)} \cdot I_{R3(\max)}$$

$$= 35 \times 0.013$$

$$P_{(R3)} = 455\text{mW}$$

A resistor with a power rating of at least twice this is recommended.

This circuit in Figure 7 was simulated and the graphs below show the results

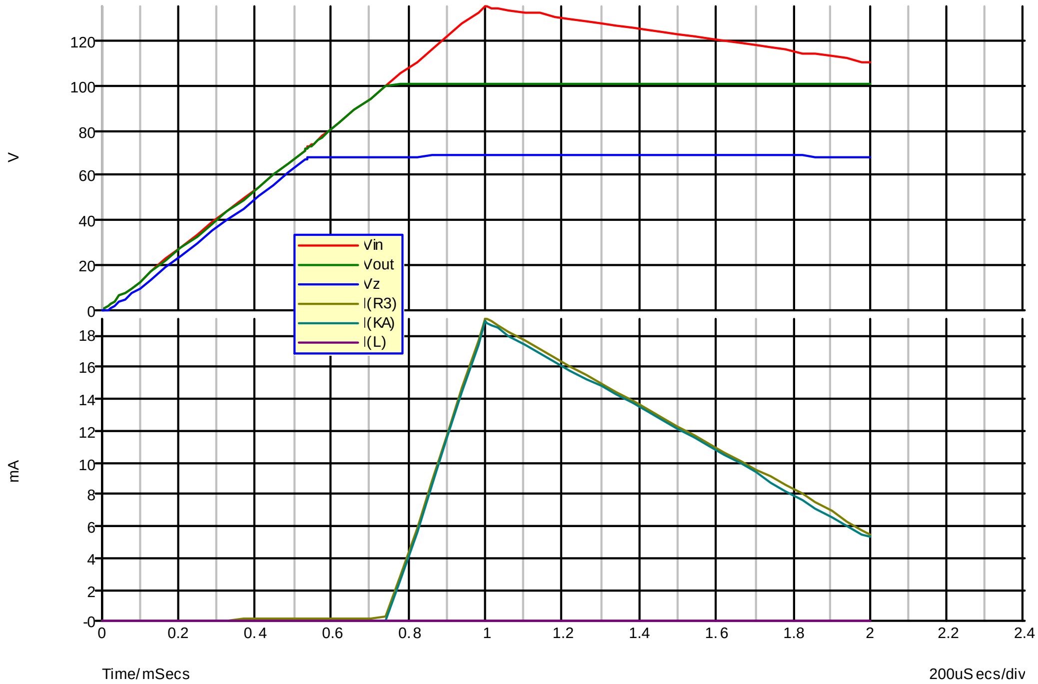


Figure 8 Reference/Zener circuit without load

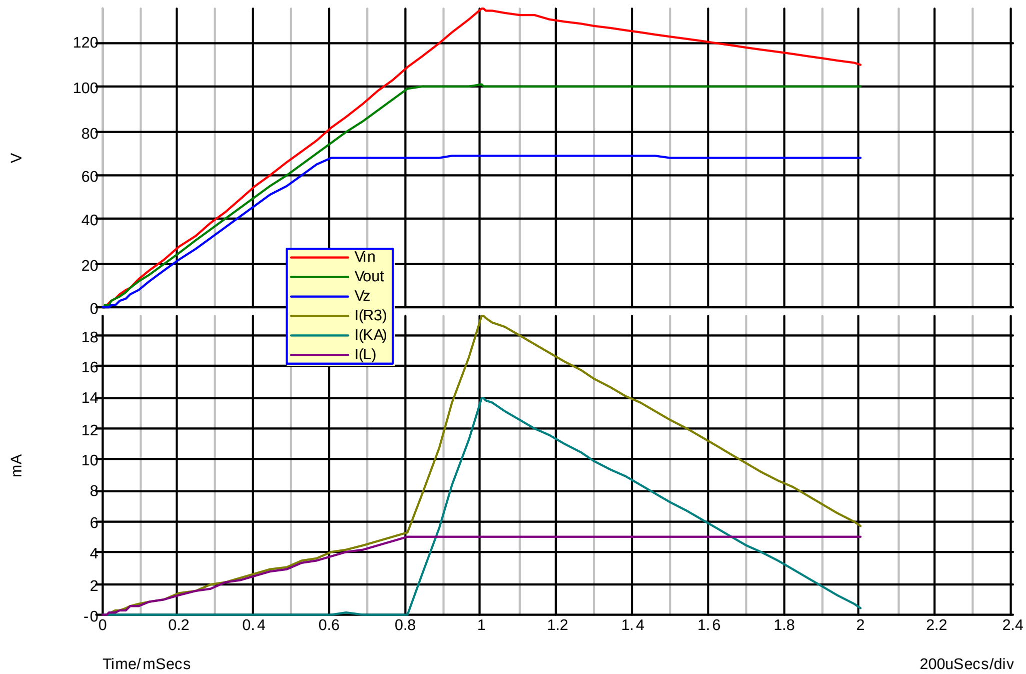


Figure 9 Reference/zener circuit with 20k load

Conclusion

The operating voltage range for references can be easily extended by using any of a number methods shown above. In most cases without compromising the accuracy or other parameters of the device.

Recommended further reading

AN58 - Designing with Shunt Regulators - *Shunt Regulation*

AN59 - Designing with Shunt Regulators - *Series Regulation*

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

AN62 - Designing with Shunt Regulators - *Other Applications*

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

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Telefon: (49) 89 45 49 49 0 Fax: (49) 89 45 49 49 49 europe.sales@zetex.com	Telephone: (1) 631 360 2222 Fax: (1) 631 360 8222 usa.sales@zetex.com	Telephone: (852) 26100 611 Fax: (852) 24250 494 asia.sales@zetex.com	Telephone: (1) 972 385 2810 www.diodes.com