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Precision voltage regulation for ultra-low noise applications

Isaac Sibson

Introduction

A simple discrete regulator circuit using Zetex voltage references and transistors can realise performance levels that are beyond IC regulators, whilst being of reasonable cost and with very little board space overhead. Although Integrated Circuit (IC) regulators dominate the marketplace through their combination of simplicity and low cost, there are situations where lower noise and better regulation are requirements for the highest level of circuit performance. In applications where performance is critical and efficiency and cost may be of a lower priority, such as data conversion in audio and video, instrumentation and low noise power for clock circuits, this discrete circuit can be immensely useful.

Zetex' expertise in small package components allows the circuit to come close to matching the power density of the IC regulator whilst maintaining higher performance through use of Zetex transistors and references.

This application note details the design of a high-performance discrete regulator and shows how to easily tailor it for new or existing designs.

The circuit

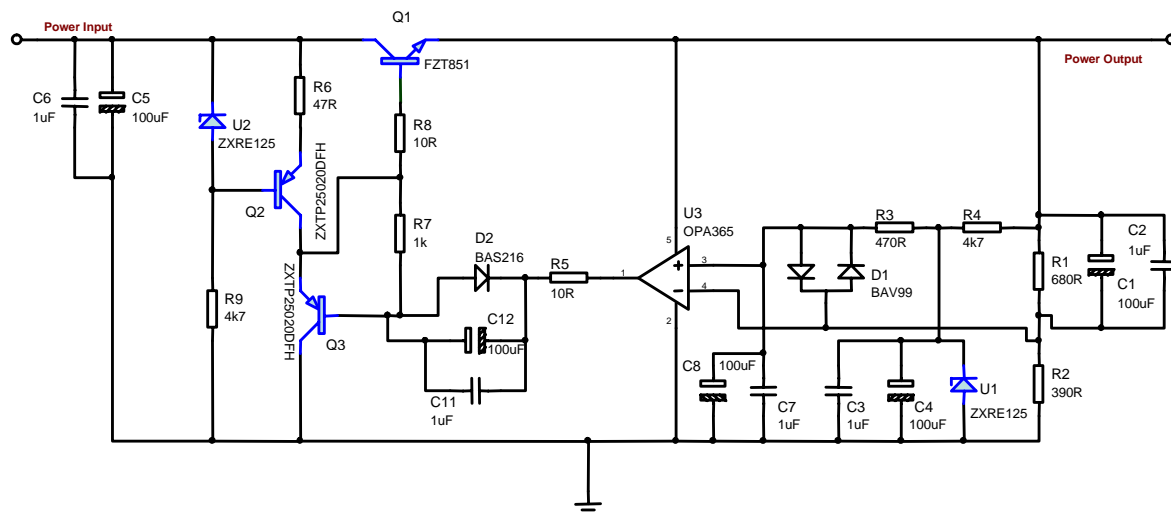


Figure 1 The discrete regulator circuit (3.3V)

Working backwards through the circuit, the output voltage is divided by resistors R1 and R2 to match the output voltage of the voltage reference U1. In the circuit with values as shown in figure 1, the reference voltage (across U1) is 1.22V, and the output voltage of 3.3V is scaled easily with standard value resistors. The capacitors C1 and C2 provide a path for the output noise to the error amplifier. The voltage reference U1 is strongly decoupled by C3 and C4, reducing reference (and thus output) noise. Dual Diode D1 acts simply to limit the size of the maximum differential input signal that may be seen by the error amplifier limits. The reference signal is again decoupled at the amplifier input in order to reduce noise yet further. U3 drives Q3 (with D2 for biasing), which then moderates the base current into Q1.

Of note in the design of the circuit is the use of the regulator circuit's output to power the error amplifier. Of course, this could give startup problems, but these are solved by the bootstrap circuit on the front end; when power is first applied, the voltage reference U2 generates a base-emitter voltage on transistor Q2, switching it on. This in turn generates a base-emitter voltage on Q1, the pass transistor, allowing the output to rise sharply until enough voltage is available for the error amplifier to operate.

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Performance

The resulting regulator circuit has excellent performance, with $3\mu\text{V}$ unweighted RMS output noise between 10Hz and 22kHz (<-120dB ref output voltage). It also offers excellent rejection and extremely low output impedance (good load regulation). These characteristics make it suitable for high-precision data conversion and isolation of sensitive parts of mixed-signal circuits.

Noise

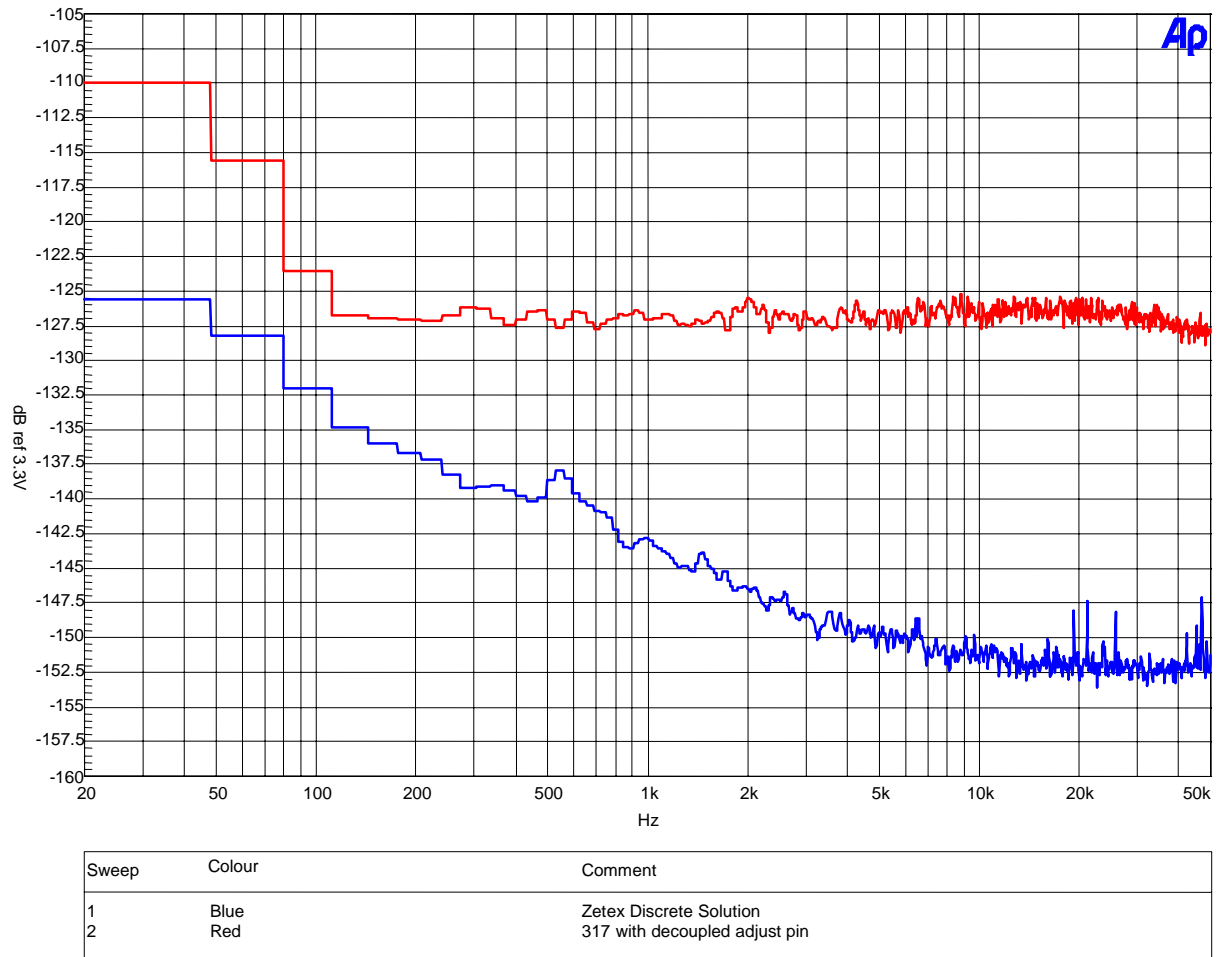


Figure 2 Output Noise FFT comparing Zetex Discrete solution with 317 type regulator

Clearly the output noise performance of the discrete regulator is significantly better than the IC regulator - the ubiquitous 317. Both circuits were operated in a similar configuration - $100\mu\text{F}$ decoupling capacitance on both input and output, and $100\mu\text{F}$ decoupling on the 317's adjust pin to match up to the $100\mu\text{F}$ decoupling the reference on the discrete circuit. For the above plot the load used was 47Ω , giving an output current of 70mA.

Output Impedance

Measuring output impedance of the regulator accurately is difficult as it is extremely low. Wire lengths to the load and return paths all have very significant effects. By connecting the load to the sense point (as it would be in a real implementation), repeatedly connecting and removing the load while the regulator is in operation yields very little change - a 6½ digit multimeter can not register a change. That puts the resultant change at less than 100µV. For a load current of 76mA, that gives a maximum output impedance at DC of less than 7.6µΩ, giving excellent load regulation.

Input Voltage

The regulator will operate down to 1V dropout, although it is advisable to allow a little more headroom. As the circuit is implemented in this note the maximum input voltage is 10V, limited by the voltage rating of the capacitors used on the input decoupling. A higher voltage capacitor would allow input voltages up to 20V, although this is not recommended due to the resulting power dissipation in the pass transistor.

Output Current

The circuit will drive up to 350mA with excellent performance as detailed. Although the circuit will drive higher currents than this (up to 800mA), performance will begin to suffer at these high current levels.

Implementation, Layout and Variations

Implementation

Of course, the ideal method of implementing this circuit is to design it into the PCB of the system that it will be part of. When doing this, the required board space is not a lot greater than that required by a 317 in DPAK packaging. In both the discrete regulator and the 317 in DPAK the power dissipation is largely constrained by the board area given over to heatsinking - the tab of the pass transistor Q1 is equivalent to the tab on the package of the IC regulator. This integration of the circuit into the design allows the output sense point (i.e. where R1 connects to the power output rail) to be moved closer to the load, lowering the output impedance of the regulator still further.

An alternative way to implement this circuit is in a stand alone "module" which can drop in place of an existing TO220 regulator. A small PCB can be produced, 11mm wide by 45mm long, with a 3-pin connector on one end, with a standard TO220 fixed regulator pin-out. This can also drop in place of a TO220 adjustable regulator such as the 317 by simply altering the configuration of the adjust resistors. However, while this option does not achieve quite the same level of performance as integrating the circuit into the target design it still offers a significant improvement over the existing TO220 regulator.

Layout

There are several points to keep in mind when laying out this circuit:

- Place the regulator circuit close to where its output is to be used.
- Solid ground-planes should be used throughout, with all vias to ground planes as close as possible to the device pins. Attention should be paid to careful circuit partitioning rather than use of split ground planes.
- If through-hole electrolytic capacitors are used then space can be saved by mounting them on the opposite side of the board. In some situations this may not be appropriate however.
- An area of copper should be given to heatsinking the pass transistor, depending on expected load. This consideration is the same as for surface-mount IC regulators.
- The sense point (Where R1 connects to the regulator output) should be connected close to the load, to minimise output impedance

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Variations

Other than the variation of how the circuit is integrated into the target system, there is also the question of different output voltages. It is easy to alter the output voltage of the circuit by applying the following formula:

$$V_{out} = V_{ref} \left(\frac{R1 + R2}{R2} \right)$$

Where V_{ref} is the reference voltage across U1. This gives three user-selectable variables which can be used to alter the output voltage: The scaling of R1 and R2 can be altered as per an adjustable IC regulator, but also the value of V_{ref} can be changed by using a larger value reference, such as ZRC250.

The suggested reference and resistor values for given voltages are:

Vout (V)	Reference	R1 (Ω)	R2 (Ω)
2.5	ZXRE125	499	475
3.3	ZXRE125	680	390
5	ZRC250	470	470

Table 1 Suggested standard voltage implementations

Other voltages between 2.5V and 5V can be realised through the use of the given formula. Going outside of this range is not possible with the op-amp used here.

The selection of voltage reference and scaling resistors R1 and R2 can also give tight control over the output voltage tolerance. Through selection of a 0.5% tolerance voltage reference (ZXRE125C) and 0.1% precision resistors the output voltage level can be set with around 0.7% accuracy without the use of trimming, comparing very well to the 4% accuracy of the 317 IC regulator.

Bill of materials

This is given for the 3.3V circuit as shown in Figure 1. U1, R1 and R2 may vary as detailed above.

Part reference(s)	Quantity	Value	Package	Comment
R1	1	680Ω	0805	Value will affect output
R2	1	390Ω	0805	Value will affect output
R3	1	470Ω	0805	Generic
R4, R9	2	4.7kΩ	0805	Generic
R5	1	10Ω	0805	Generic
R6	1	47Ω	0805	Generic
R7	1	1kΩ	0805	Generic
R8	1	10Ω	1206	Generic
C1, C4, C5, C8, C12	5	100μF	2.0mm pitch Radial	Rubycon 10ZL100M5X11
C2, C3, C6, C7, C11	5	1μF	0805	Murata GRM21BR71C105KA01L
U1, U2	2	ZXRE125	SOT23	Zetex Different tolerances available
U3	1	OPA365	SOT23-5	TI
Q1	1	FZT851	SOT223	Zetex
Q2,Q3	2	ZXTP25020DFH	SOT23	Zetex
D1	1	BAV99	SOT23	Generic
D2	1	BAS216	SOD110	Generic

Table 2 Bill of materials for 3.3V variant

Conclusion

A linear adjustable voltage regulator circuit with a noise level of less than 3μV can be constructed using standard Zetex parts and precision, low-noise voltage reference. It is scalable over a range of input and output voltages and current values. For circuits where low noise, high load regulation stability and precise tolerance is required, this discrete circuit significantly outperforms off-the-shelf IC regulators.

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Europe	Americas	Asia Pacific	Corporate Headquarters
Zetex GmbH Kustermann-park Balanstraße 59 D-81541 München Germany Telephone: (49) 89 45 49 49 0 Fax: (49) 89 45 49 49 49 europe.sales@zetex.com	Zetex Inc 700 Veterans Memorial Highway Hauppauge, NY 11788 USA Telephone: (1) 631 360 2222 Fax: (1) 631 360 8222 usa.sales@zetex.com	Zetex (Asia Ltd) 3701-04 Metroplaza Tower 1 Hing Fong Road, Kwai Fong Hong Kong Telephone: (852) 26100 611 Fax: (852) 24250 494 asia.sales@zetex.com	Zetex Semiconductors plc Zetex Technology Park, Chadderton Oldham, OL9 9LL United Kingdom Telephone: (44) 161 622 4444 Fax: (44) 161 622 4446 hq@zetex.com

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