Precision System Technologies
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Reducing Power Supply Ripple and Noise

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Introduction

The ripple and noise from ordinary power supplies is often a limitation in working with low-level signals. While the low-noise buried zener and reference filtering in the LM723 [1] allow it to produce 2.5 uV rms noise from 100 Hz to 10 KHz, the bandgap references [2] in other regulators are far noisier. For example, the LM2940C [3] specification allows up to 1,000 uV of rms noise from 10 Hz to 100 KHz.

The rms output noise of the popular LM117 [4] voltage regulator is specified at 30 microvolts per volt of output from 10 Hz to 10 KHz. A 5 volt supply can have 150 microvolts of wideband noise. The ripple rejection is from 60 to 80 dB, so with one volt of ripple at the input, the output can have 100 to 1,000 microvolts of ripple. Bypassing the adjustment terminal to ground can improve the ripple rejection, but this may not be done in cheaper power supplies.

While good design techniques can reduce the noise and ripple in regulators, they may not be implemented properly or may be omitted entirely.

One example is low-cost wallwart power supplies. These can be a convenient source of DC, but they can be quite noisy.

Even when all the techniques are used to minimize regulator noise, the remaining noise and ripple can degrade the performance of sensitive electronics, such as precision pll's and low-level amplifiers. Here is a brief overview of different methods of reducing it.

1. Cancellation Method

In his article "Finesse Voltage Regulator Noise" [5], Charles Wenzel discusses several methods of reducing ripple and noise. Figure 1, reproduced below, shows a method of canceling ripple by applying an equal and opposite voltage to the load side of a 15 ohm series resistor.

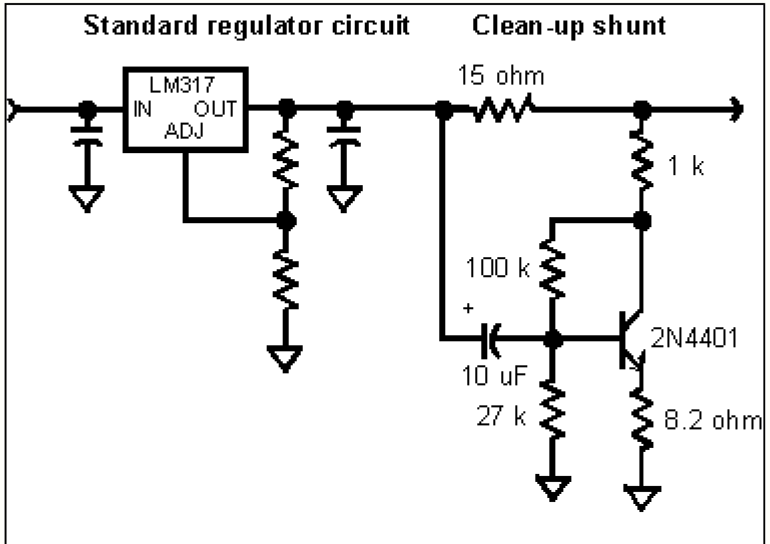
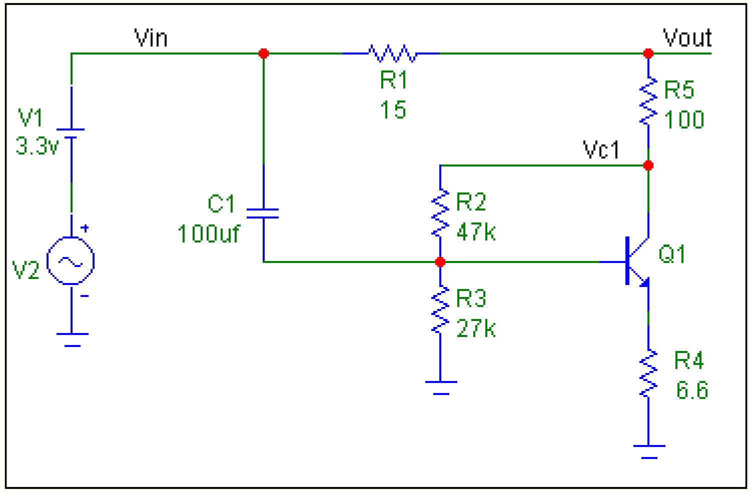
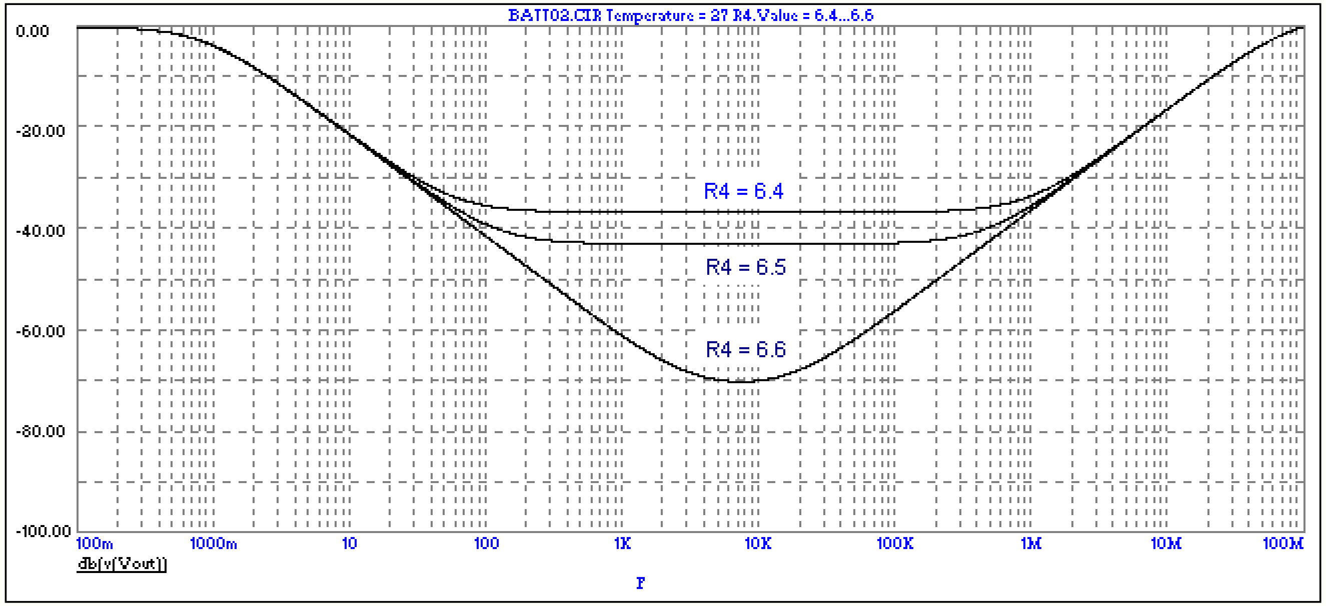


Figure 1: Clean-up circuit for low current loads.

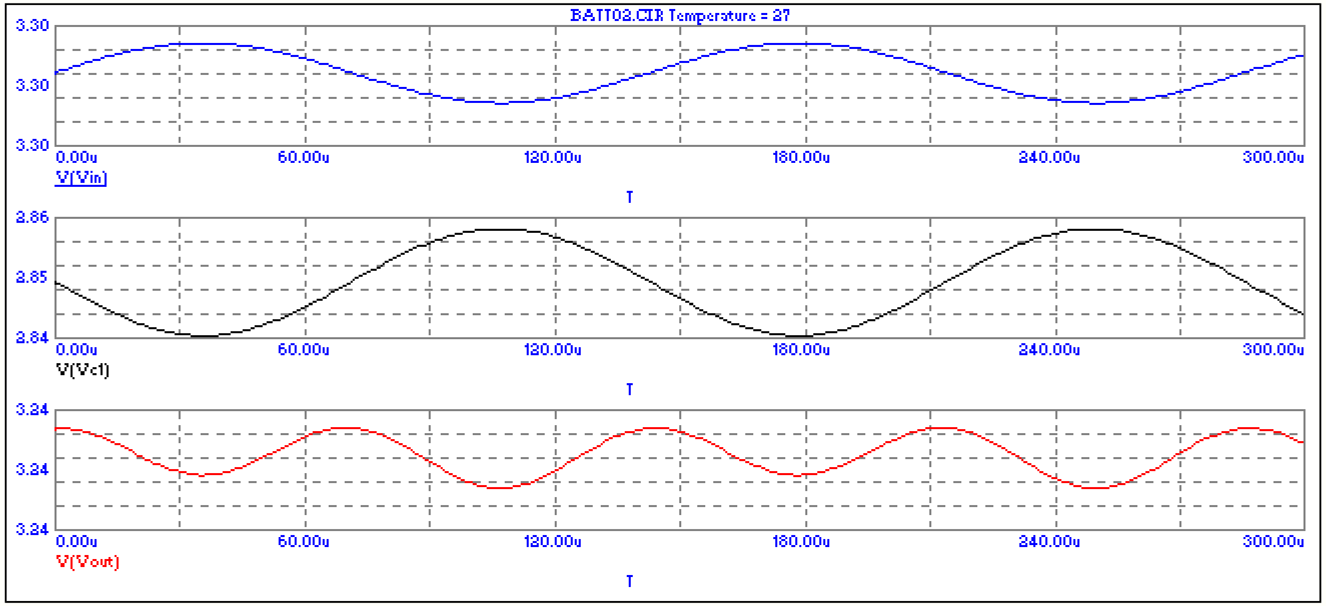
The circuit was modified to work in a power supply for a 3.3 volt PLL. The changes are shown below.



As with any cancellation method, the attenuation is extremely sensitive to changes in load impedance, ambient temperature, and component drift over time. This could cause unexplained variations in system performance that could be difficult to diagnose. The graph below shows the attenuation as R4 is changed from 6.4 ohms to 6.6 ohms. The attenuation at the null point changes over 30 dB for a 3% change. Since the same change could easily occur with normal temperature variations, we conclude this circuit is too unstable to be very useful.

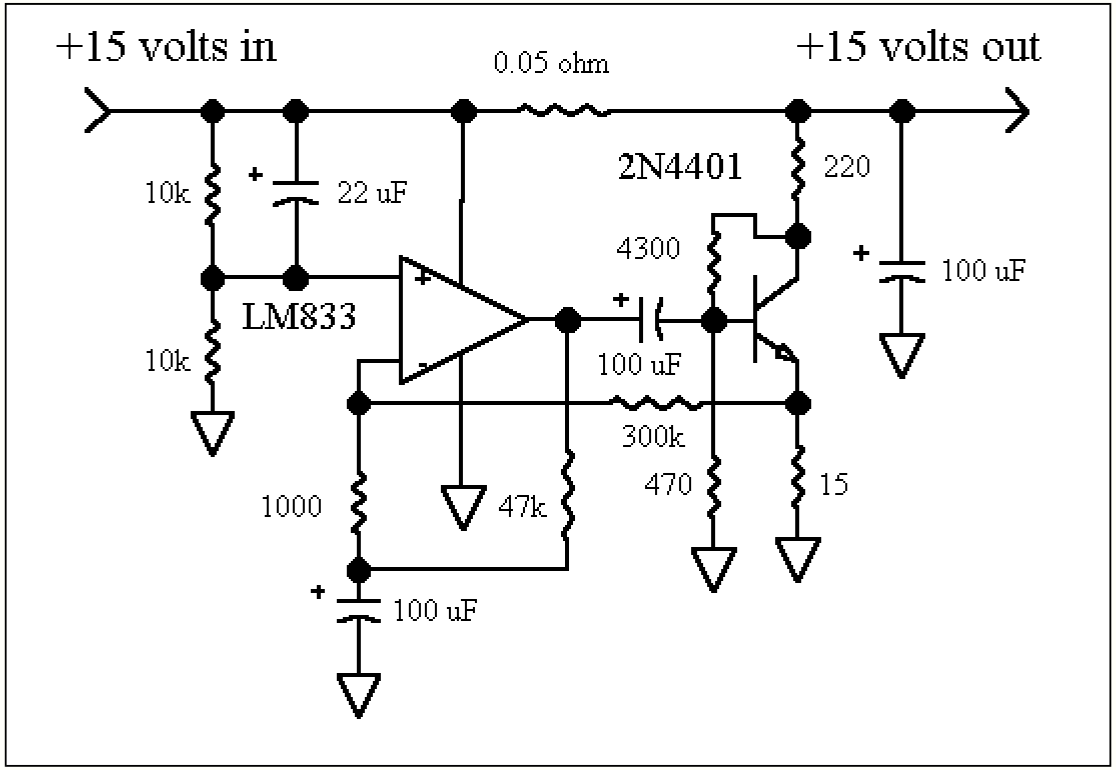


Distortion in the inverter is not canceled by feedback. The waveforms in the plot below show a 2 millivolt p-p input signal at 7 KHz (Blue), the voltage at the collector of Q1 (Black), and the resulting output signal (Red). Strong second harmonic distortion is evident in the output signal, which limits the maximum available attenuation. This distortion is not accounted for in the frequency response graph.

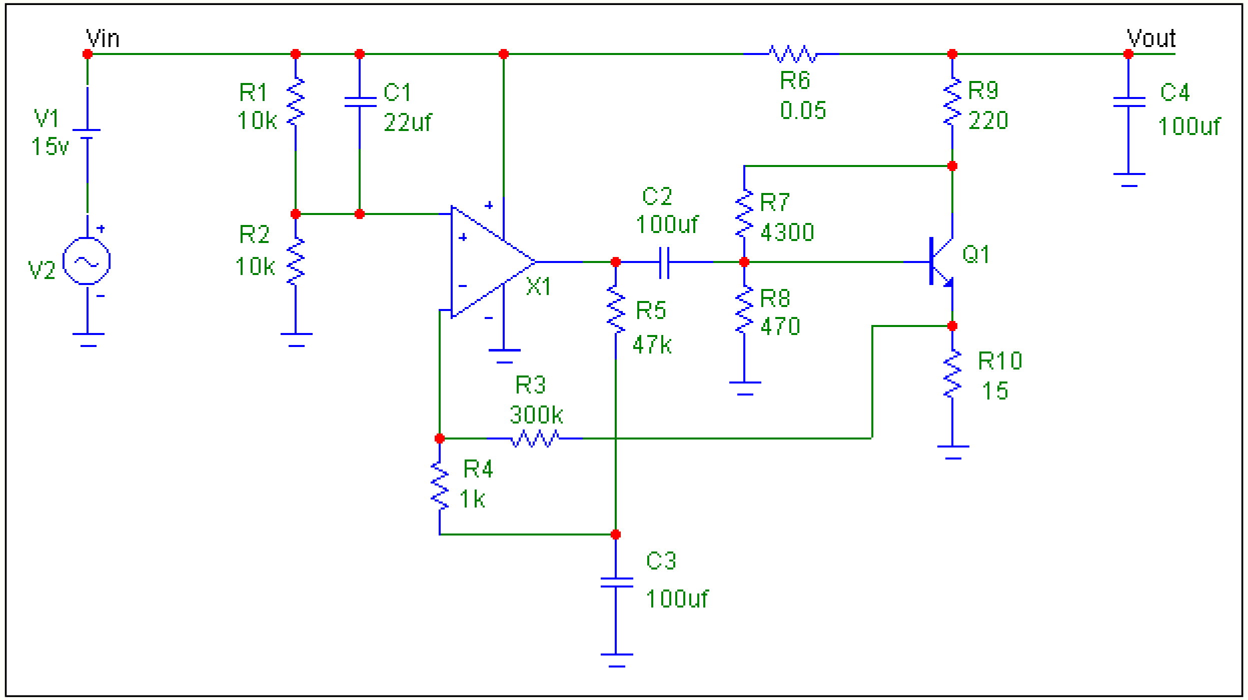


Op Amp Version

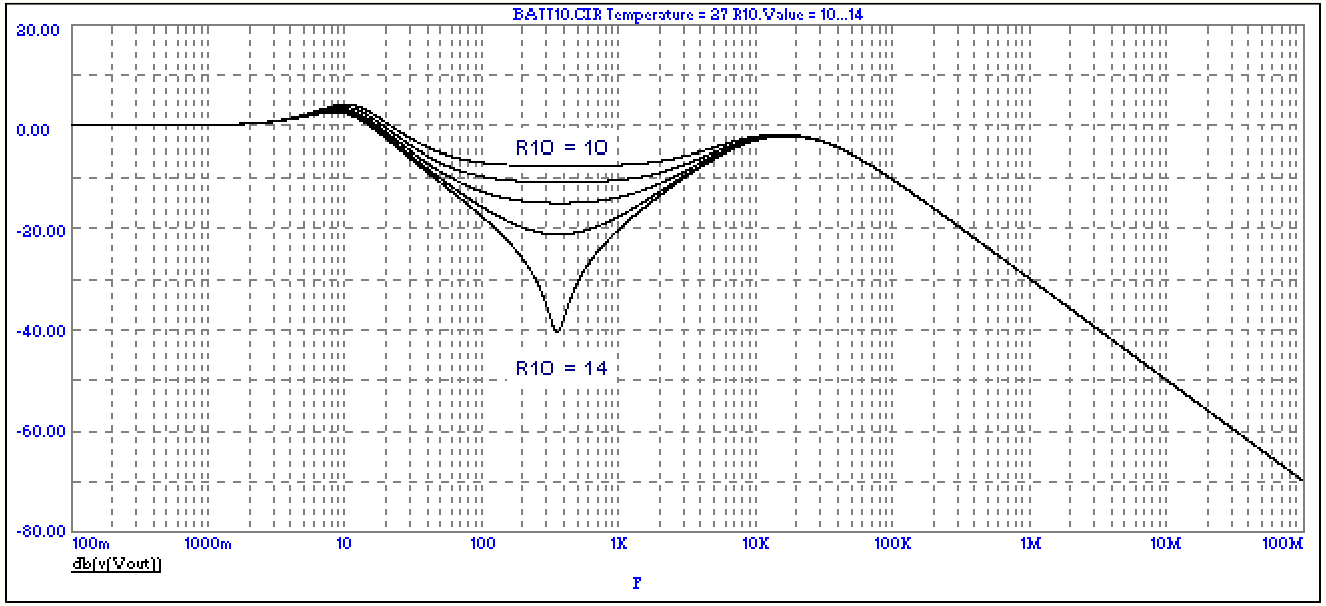
Wenzel also describes a more complicated op amp version shown below.



It was entered in SPICE as shown below.



The attenuation as R10 is stepped from 10 ohms to 14 ohms is shown below.



The null has moved down from about 8 KHz to 130 Hz and shows less attenuation than the single transistor version in Figure 1. In addition, the op amp now contributes its own broadband noise to the output.

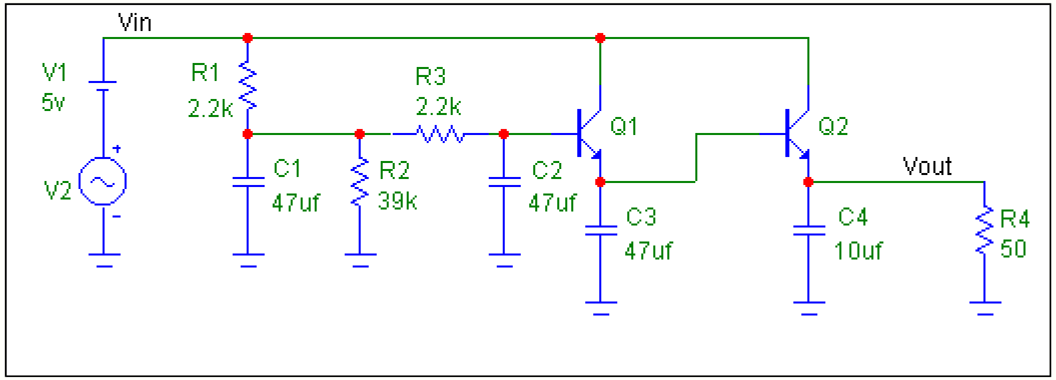
Since the cancellation method relies on perfect matching, which is difficult to achieve, no further attempt was made to optimize this circuit.

2. RC Darlington Emitter Follower

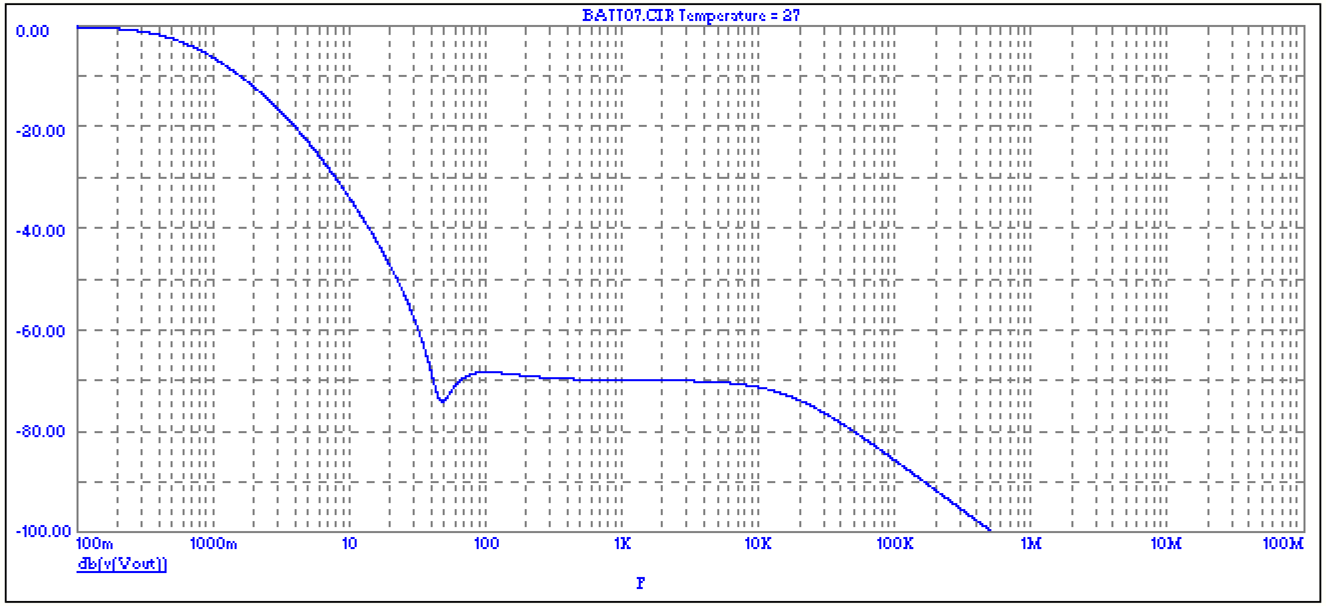
The above methods are limited to low-current loads due to the voltage drop across the power supply series resistor.

A three-stage RC filter in a Darlington emitter follower allows higher currents and provides excellent performance over a wide frequency range. It needs about 1.4 volts of headroom. Resistor R2 is used to trim the output voltage to the desired value. The output voltage will change with load and temperature, but satisfactory operation can be obtained over a wide range.

The output impedance of the circuit shown is 1.29 ohms, as calculated in SPICE.



With the values shown, this method provides good attenuation from 50 Hz to 100 MHz. The attenuation floor between 100 Hz and 10 KHz is determined by the impedance of transistor Q2, which will vary from one transistor to the next.



The performance above 10 KHz is determined by the ESR of the filter capacitors and the circuit layout. In order to improve the performance at higher frequencies, multiple ceramic capacitors can be added in parallel with the electrolytic. These are usually provided by the bypass capacitors in the following circuitry. However, this can easily create additional resonances with the capacitor and trace inductances. Some nodes may show large resonances and others litle or none, so care must be taken to examine the entire supply structure over the complete frequency range of interest plus harmonics, and any clock frequencies plus their harmonics. (Yes, Virginia, that can be a lot of work. But you have to do it. Every node. You might be shocked by what you discover. And do it again every time you make a change to the bypassing.)

The ultimate noise floor is determined by transistor noise. For the 2N4401 (2N2222), the typical noise is claimed to be about 1 nanovolt per root-hertz or about 1uV rms in a 1 MHz bandwidth. The noise will vary with output current and transistor type.

Fault Protection

1. **Short-Circuit at the Output:**

   There is no protection against output short circuits. Current limiting must be provided in previous stages.

2. **Short-Circuit at the Input:**

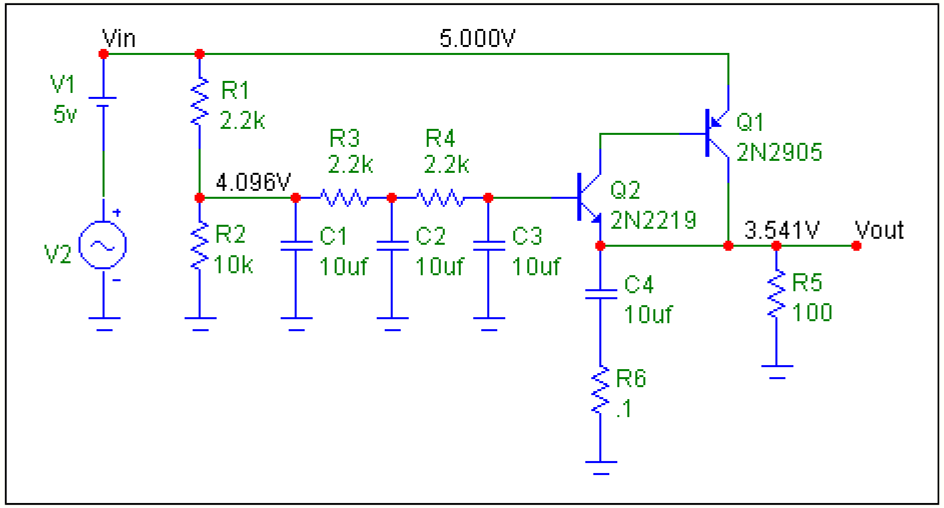
   A short on the input supply will forward-bias the base-collector junctions and discharge the 47 uF capacitors. For low output voltages, the energy is small and is not likely to cause damage.

   The 10 uF capacitor Q4 will discharge through the load. If the output voltage is above 6 volts, it may reverse-bias the base-emitter junction of Q2. A protection diode should be added to prevent this.

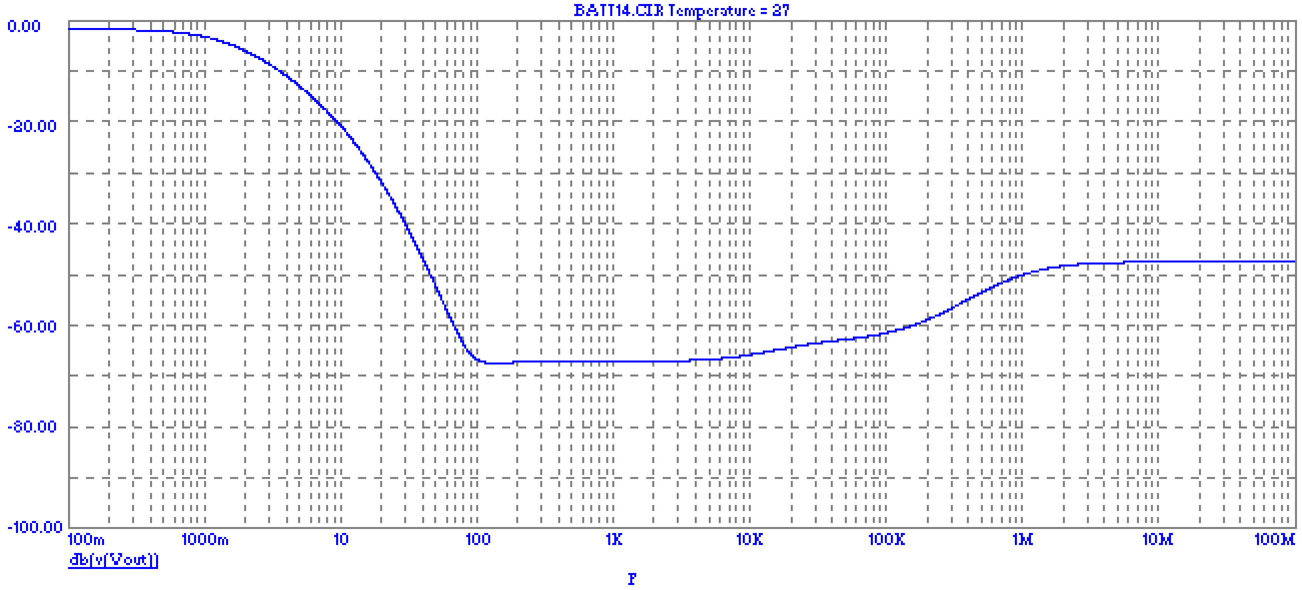
3. Complimentary Follower

A Complimentary Follower (see also Sziklai pair) has advantages over the conventional Darlington. The output noise and drift are cut in half since Q1's contribution is canceled by the negative feedback from transistor Q2.

Resistor R2 can be adjusted to set the output voltage about 1.4V below the supply voltage. The output impedance of the circuit shown below is 1.31 ohms, as calculated in SPICE.

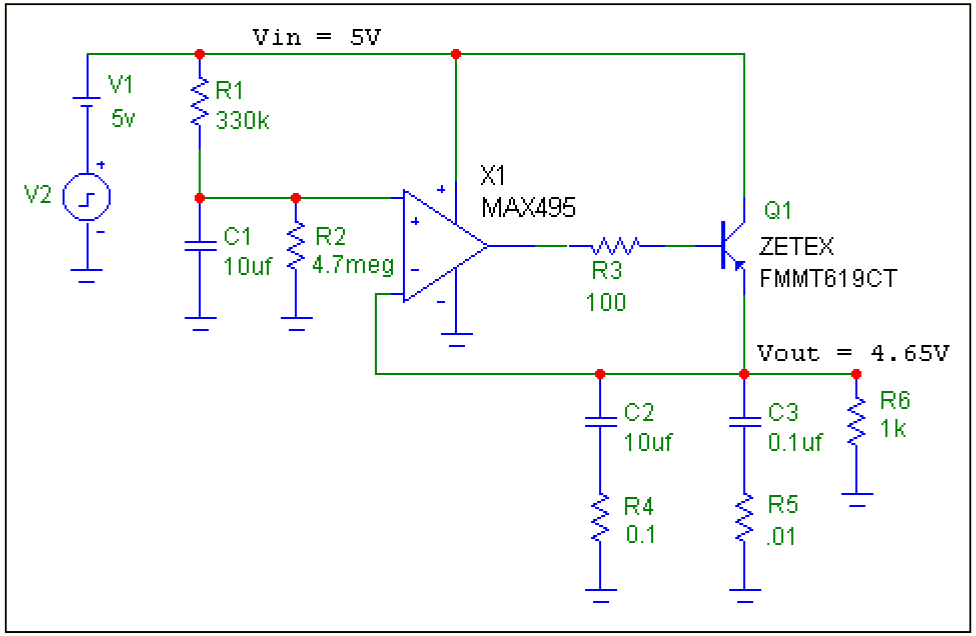


The attenuation is similar to the Darlington. The attenuation floor between 100 Hz and 100 KHz is determined by the loop gain, which is device-dependent. The response above 100 KHz is largely determined by the ESR of the output capacitor C4.



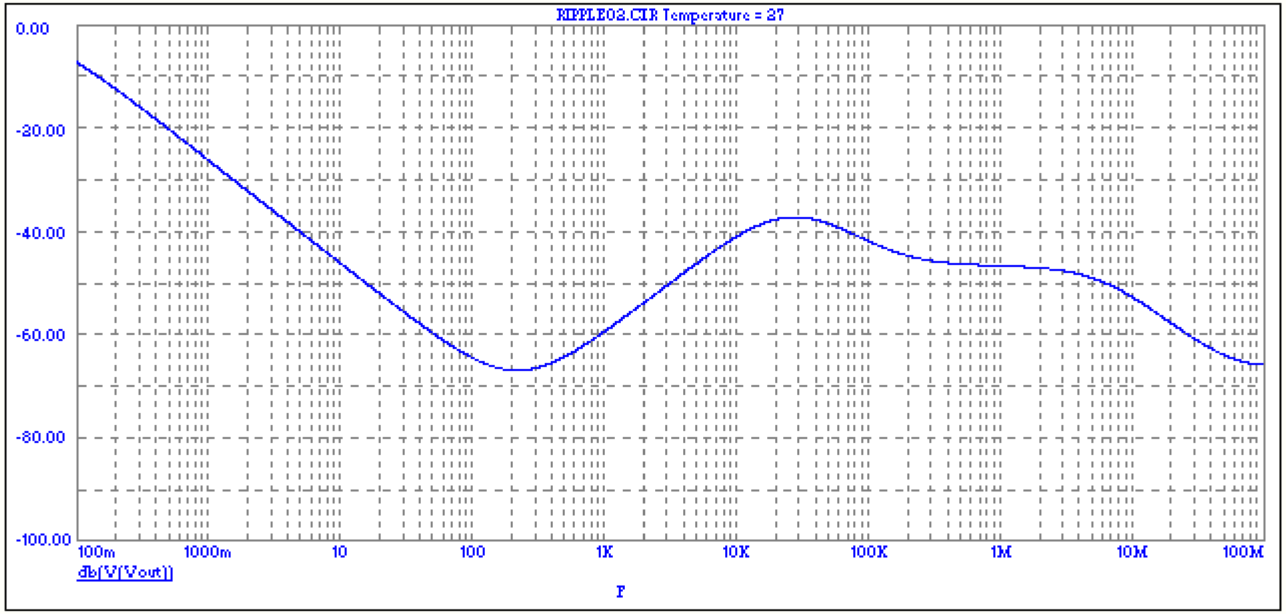
4. NPN Pass Follower

A follower using a NPN pass transistor can supply currents up to 1A with a low, fixed voltage drop. In the example shown below, the output is 93% of the supply voltage. In the example shown, a MAX495 [6] Rail-to-Rail Op Amp is used as the control element. See the Maxim Application Note 899 [7] for more details. NOTE: The polarity of the op amp input shown in Figure 1 in the Maxim App Note 899 is wrong. The plus and minus input pins need to be swapped.

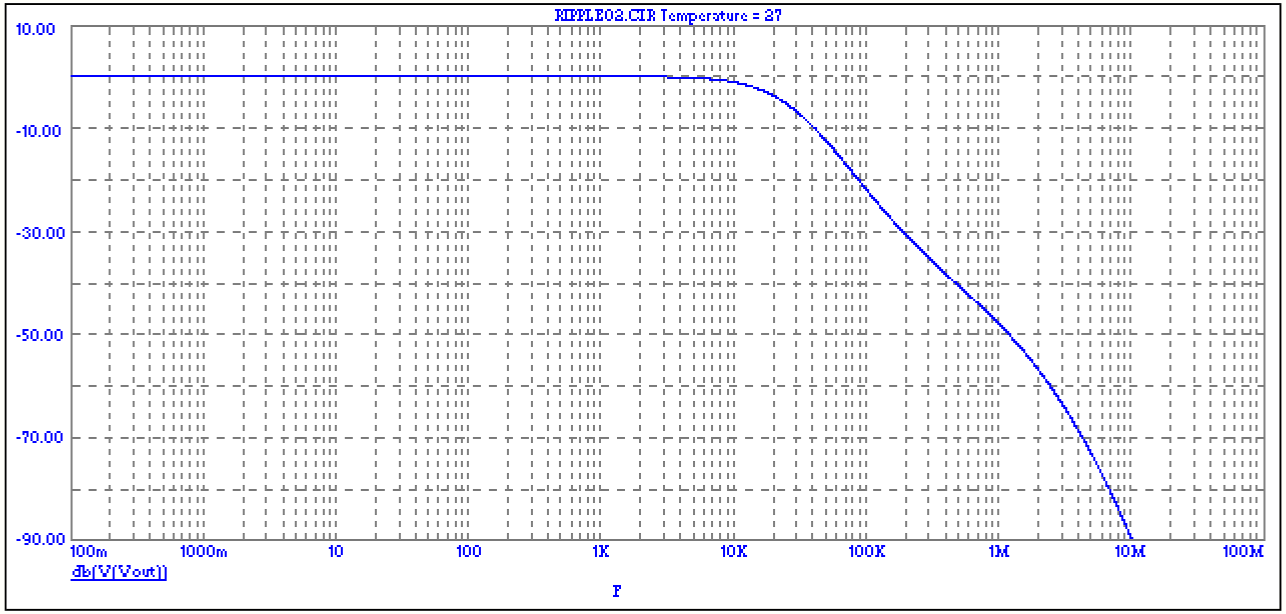


The attenuation is shown below, and more or less meets the Maxim specification of 40dB attenuation from 100Hz to 20KHz. The response forms a null where the left part is the attenuation of the RC filter. The rising portion on the right occurs as the decreasing gain and increasing phase shift of the op amp degrades the cancellation of the feedback signal. The cure is to use a faster op amp, but it may have more internal noise.

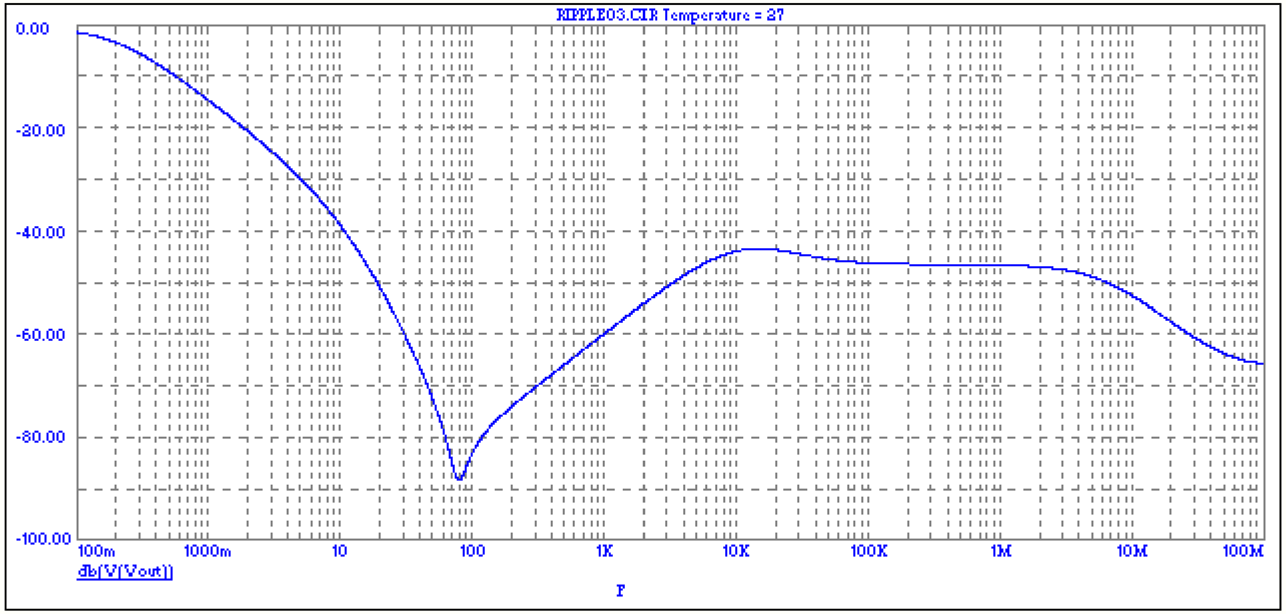
The performance above 10 KHz is determined by the ESR of the output capacitors C2 and C3.



The MAX495 is specified at 25 nV/sqrt(Hz), or approximately 2.5 uV rms from 1 to 10 KHz. This is similar to the LM723 [1]. The plot below shows how the noise appears at the output of the regulator:



Adding more RC sections to the ripple filter (R1C1) can increase the notch depth, but have little effect above 1 KHz.



Summary

1. The cancellation method is capable of high attenuation at a specific frequency, but it is very sensitive to component drift. The op amp version has the same problem and contributes additional noise to the output.

2. The RC Darlington offers low sensitivity to component variation and excellent attenuation at typical line frequencies. It can supply high current, but has a large voltage drop and temperature coefficient. The noise floor is determined by the transistors.

3. The Complimentary Follower has similar voltage drop and input and output impedance as the Darlington, with half the noise and thermal drift.

4. The NPN Pass Follower can supply moderate ripple reduction for load currents up to 1A with a low voltage drop. However, the input noise of the op amp appears at the output from DC up to the cutoff frequency of the regulator. Depending on the op amp, the resulting noise could be equal to or greater than the original signal.

Conclusions

Overall, the RC Darlington and Complimentary Follower give the highest ripple attenuation but are among the poorest for regulation and thermal drift.

The various cancellation methods give sharp notches with poor attenuation on either side, and require extremely tight tolerances on gain and component values that are unlikely to be met in practice. Cancellation has no effect on the strong harmonic distortion produced in the error amplifier due to low values of the feedback resistor. However, if the ripple is at a single frequency and there is no other noise to consider, cancellation might be an effective approach.

Circuits using op amps tend to have poor performance at higher frequencies due to decreasing loop gain.

All ripple reduction circuits are likely to be sensitive to pcb trace impedance, capacitor ESR, and layout and grounding techniques. In order to improve the ESR at higher frequencies, multiple ceramic capacitors can be added in parallel with an electrolytic. These are usually provided by the bypass capacitors in the following circuitry. However, this can easily create additional resonances with the capacitor and trace inductances. Some nodes may show large resonances and others litle or none, so care must be taken to examine the entire supply structure over the complete frequency range of interest plus harmonics, and any clock frequencies plus their harmonics.

Links

[1] National Semiconductor LM723

[2] The Best of Bob Pease "The Design of Band-Gap Reference Circuits: Trials and Tribulations"

[3] National Semiconductor LM2940C

[4] National Semiconductor LM117

[5] Charles Wenzel, "Finesse Voltage Regulator Noise"

[6] Maxim Data Sheet MAX495 (Obsolete)

[7] Maxim Application Note 899, "Low-power Circuit Reduces Vcc Audio Ripple by 40dB"

Low Noise Switchers

Linear regulators tend to waste power due to the several volts required for the pass device. Depending on system requirements, the Linear Technology Low Noise Switching Regulators can give ripple values of less than 100uV, which is comparable to or less than many linear regulators. These switchers reduce noise by controlling the slew rate of the switching waveform.

1. The first model uses a conventional transformer with a push-pull primary and diode rectifiers on the secondary:
   LT1533 Ultralow Noise 1A Switching Regulator.

2. The second model is a fixed frequency current mode switching regulator suitable for Boost, Flyback, Inverting, Cuk, etc.:
   LT1534 Ultralow Noise Switching Regulator.

The following app notes are also useful:

AN70 A Monolithic Switching Regulator with 100uV Output Noise

snan70 (corrects pin number errors in AN70)

AN75 Circuitry for Signal Conditioning and Power Conversion

AN118 - High Voltage, Low Noise, DC/DC Converters

LT1533 Ultralow Noise Switching Regulator for High Voltage or High Current Applications

It might be interesting to see if the LT1533/LT1534 can close the loop around one of the wideband filters, such as the Complimentary Follower. This would give the ne plus ultra of low noise, high efficiency supplies.

Acknowledgments

Thanks to Jim Thompson and Helmut Sennewald for helpful discussions on vendor-supplied SPICE models.
