Circuit Design Clinic
DEC 2006

Brainstorm Session: High-Efficiency Linear Amplifier
by Dennis L Feucht

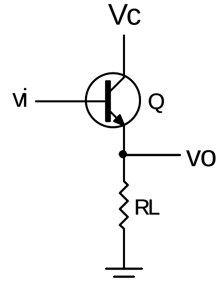
The way the Circuit Design Clinic usually works is that you send me an electronics circuit (or circuit-related) problem and I try to provide you a somewhat decent solution to it. The alternative format is that problems encountered on a particular project are surveyed and solutions discussed. This scheme assumes a category of problems that I call *standard engineering*, problems of a kind that have known solutions. The parameters and other features of your particular problem might be unique, but the kind of problem posed is not novel. Solving it will not break into new, unexplored territory on the electronics knowledge landscape.

The other category of problems is those that have no known solutions, or for which alternative, possibly better, solutions are needed. If a reader were to ask: "How do I solve the problem of communicating through the earth to the other side of the planet?" I could not provide any known, elegant solution other than the existing long-way-around methods. (And not being well-oriented to the frequency domain, I wouldn't even be good at that.) However, I could instead go into brainstorming mode and propose some ideas that might lead to something novel -- maybe neutrino-based communications. (But how, you ask, without using too much carbon tetrachloride in the detector!) This category of problem is, in contrast to standard engineering, a state-of-the-art, or leading edge, or simply an *engineering research* problem, a problem not ever really solved (or solved well) before.

This category of problems can be included in the Clinic by an occasional brainstorm session. This is the first. In it, I offer prolusive ideas. Some of them are admittedly wild, maybe obviously unappealing to better minds. Maybe one or more ideas will act as stepping-stones to the real breakthrough that *you* discover instead. Or maybe my writing and your reading will stir the creative tendencies in both of us, and it will indirectly impact unrelated problems. Or perhaps the exercise will be entirely misconceived, misguided, and a waste of time. What is intriguing about this category of problems is that we do not know which it will be. Creativity and exploration involve a tentative groping forward, and can result in wasted time and effort on a dead end or in a breakthrough discovery or invention. So with that in mind, here we go…

High-Efficiency Linear Amplifier Concept

The problem to be solved here is to increase the efficiency of linear power amplification. Switching amplifiers, though highly efficient, can also be noisy in precision applications such as audio test and measurement or nano-positioner control loops. The basic problem is the excessive power dissipation in the transistors of the output stage. The basic output circuit illustrates the problem.



The power dissipation of transistor Q, p_D, is:

$$p_D = (V_C - v_o)\cdot\left(\frac{v_o}{R_L}\right) = \left(\frac{V_C}{R_L}\right)\cdot v_o - \frac{v_o^2}{R_L}$$

The derivative of p_D with respect to v_o, when set to zero, results in $v_o = V_C/2$. At this output voltage maximum power is dissipated. It corresponds to a current of $i_o = (V_C/2)/R_L$. Then maximum power dissipation by Q is:

$$\max\ p_D = \frac{V_C}{2}\cdot\frac{V_C/2}{R_L} = \frac{1}{4}\cdot\frac{V_C^2}{R_L}$$

This power dissipation of Q at maximum power equals the output power and corresponds to an efficiency of 50%. This occurs at the midrange operating point on a load-line plot on the transistor characteristic curves (i_C versus v_{CE}, or i_D versus v_{DS}), where both voltage and current are half their axis-intercept values of V_C and V_C/R_L. The output power is:

$$p_o = v_o\cdot\frac{v_o}{R_L} = \frac{v_o^2}{R_L}$$

Total supplied power is:

$$p_C = V_C\cdot\frac{v_o}{R_L}$$

Then the efficiency can be expressed as:

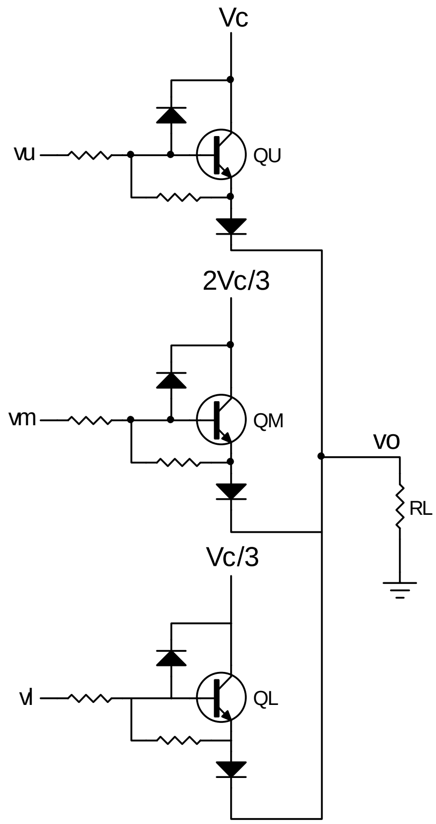
$$\eta = \frac{p_o}{p_C} = \frac{v_o^2/R_L}{V_C\cdot(v_o/R_L)} = \frac{v_o}{V_C}$$

From this simple expression it is evident that as v_o approaches V_C, the efficiency increases toward the ideal of 100%. The goal is to make V_C closer to v_o.

One approach to this has been to cause the power supplies to track along with the signal. But this bootstrapping method has obvious limitations and only pushes the efficiency problem back into the supply. (If it is a fast switching supply, then maybe that is not a bad idea.

But then, why not use a switching amplifier too?) Also, if the amplified signal is faster than the response of the power supply, then it will not follow fast waveform changes.

The idea I offer here is to use multiple, stacked transistors, each operating only within its range of output voltage, and each having a supply voltage slightly above its range. For instance, consider a three-segment transistor circuit, shown below.

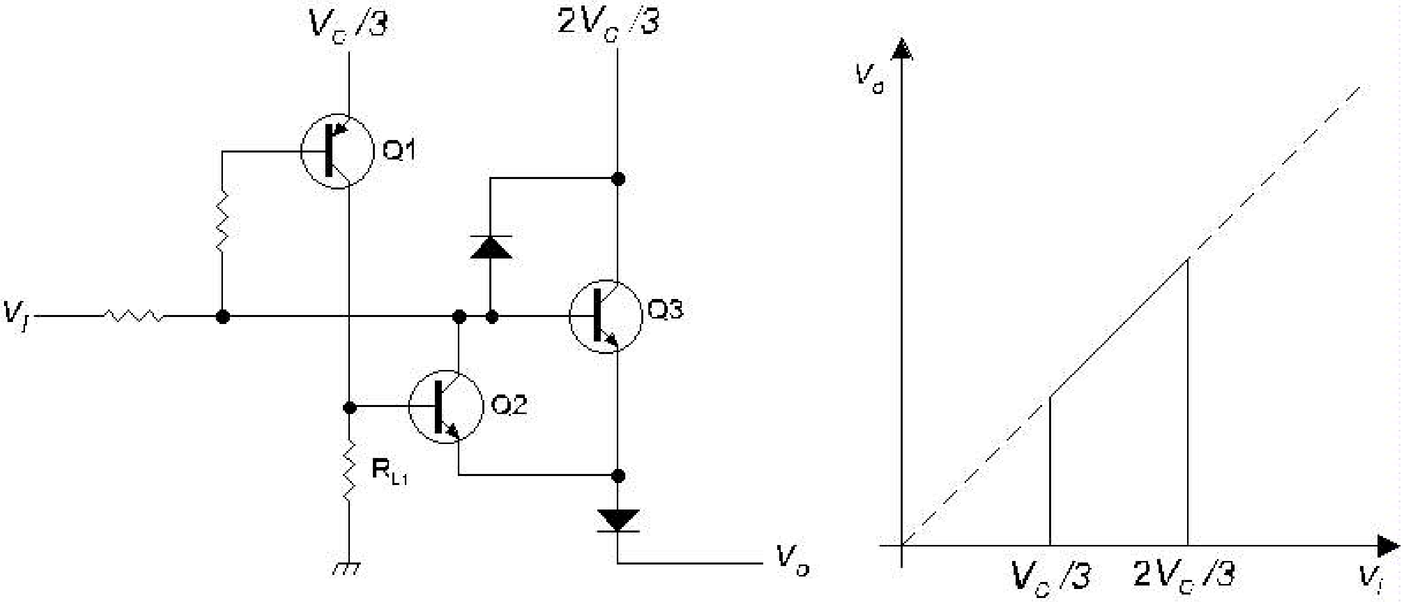


The three different supplies are justified in regard to efficiency in that a low-noise linear supply can easily be designed to have transformer secondary winding taps to provide multiple voltages. Regulators for each supply are required, increasing the cost, but the efficiency is not degraded. Of course, efficiency has its price.

The series output diodes of this circuit allow whichever transistor has the highest input voltage to conduct, and the others are cut off by the diode (wire-OR) clamping. The base-emitter shunt resistors are a turn-off path for the transistors. The input R and diode clamps the base voltage to the supply voltage, to keep the emitter from following above the supply. This allows the higher-voltage segments to conduct, one at a time.

A design challenge for this scheme is to supply the correct input voltages to the segments. The simplest scheme to examine is to connect the inputs together to v_i. As v_i increases lower-voltage segments turn off successively, but the segments at or above the input voltage conduct in parallel, more or less. This reduces efficiency because, for example, if v_i is in the middle segment range, V_{CE} of the upper-segment transistor, QU, would be excessive. A more elaborate input circuit is required for one-of-*n* segment operation.

The following modified segment circuit allows turnoff of a segment when v_i is below its range.



Turn-off is accomplished by Q1. When v_i approaches $V_C/3$, Q1 and Q2 turn off, allowing the Q3 power BJT to follow v_i for the middle segment. The output diode disconnects Q3 above $2V_C/3$. Each segment circuit can be identical, except for supply values. The lowest-voltage segment does not need the Q1 turn-off circuitry because there is no voltage less than its segment for which it needs to be off.

Closure

This circuit hack in the quest for a more efficient linear amplifier has not been built or even simulated. It is a brainstorm, an idea that appears to have some protreptic value. Details remain to be worked out. For one, the segment crossover characteristics need further study, to make sure that at least one segment is fully on all the time. Some overlap will not appreciably degrade efficiency. This kind of circuitry has similar crossover characteristics as the familiar complementary emitter-follower output driver, of which I have done some investigation, as described in my book *Analog Circuit Design* (see http://www.innovatia.com). The dynamics of segment switching also needs some further thought. And, for low-distortion circuits, the segment crossovers must also maintain the same gain as within segments, which must also have matched gains.