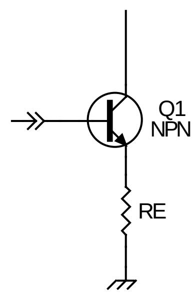
High-Voltage Amplifier Circuits

by Dennis L Feucht

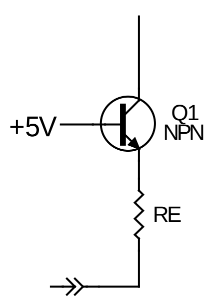
Some linear amplifiers require an output voltage range that is large relative to the rest of the system. Some applications are: Power pulse amplifiers, motor drivers, piezoelectric transducer drivers, oscilloscope deflection-plate drivers, on-chip programming supplies, analog computers, EL panel and display supplies, and audio power amplifiers. Whether it is 12 V or 1.2 kV, special considerations arise when transistor breakdown voltage becomes a critical design parameter. This article presents circuit alternatives for high-voltage (HV) amplifiers, and their relative merits.

Translator Stage

Usually near the amplifier input is a stage of amplification that performs the function of voltage translation -- of accommodating HV at its output node. Two possible circuits are the common-emitter (CE) and common-base (CB) transistor configurations. (Although BJTs will be used here, FETs can also be applied, taking into account relevant differences between them.) The CE translator is shown below in simplified form.



If a negative supply is available, the emitter resistor (R_E) can be returned to it, allowing the input voltage at the base to extend to ground. Without R_E, the collector voltage of Q1 can extend down to near-ground, to the onset of collector saturation. With even a small (>33 Ω) R_E, the input circuit is more linear and less loop gain is required to stabilize it. With any sizeable value of R_E, the input resistance is relatively high, which is required for a voltage-input amplifier. Ideally, a negative supply of -5 V to -12 V is much greater than the 0.7 V of the base-emitter junction, and allows stable biasing of the transistor at a given current.



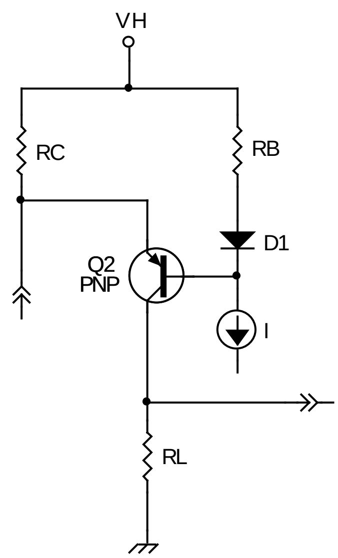
An alternative to the CE is the CB, shown above. Its input resistance is $R_E + r_e$, where r_e is the dynamic emitter resistance of Q1. The base is returned to a convenient supply voltage, which can also be synthesized with a resistive divider. (Then, the equivalent base resistance, R_B, adds to the input resistance as $R_B/(\beta + 1)$. The CB alternative is inherently faster than the CE because the Miller effect is eliminated. However, the collector of Q1 is limited in range on the bottom end by the base voltage, and cannot swing down to near-ground. The lower the base voltage is made, the analogous CE situation with a grounded R_E is approached. The base voltage needs to be large enough to allow R_E to dominate input resistance, for both bias and incremental gain stability.

Because transistor breakdown voltage is an issue, the CB has the clear advantage over the CE. The lower the base resistance, the higher the voltage that can be sustained at the collector. (A CB also has a higher dynamic collector resistance, allowing larger load resistors without sacrificing gain.)

Next Stage

What goes up must come down -- sometimes. Unless the HV amplifier is like an oscilloscope deflection amplifier, for which the output is usually at an elevated dc value, the high voltage that the translator stage can accommodate must also allow for low voltage at the low end of the output-voltage range. Assume that the design needs to accommodate at least ground in the output range, if not lower.

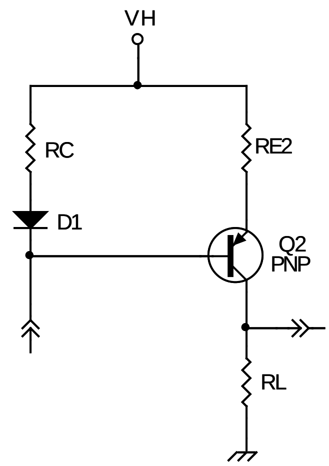
Two circuit alternatives get back down to ground. The common-base, shown below, forms a complementary cascode stage with a CE translator. R_C is kept small, to maximize the upper end of the output voltage range at the collector. R_B, diode D1 and the current source provide a base voltage that



tracks variation in V_{BE}(Q2) with temperature, to a first approximation. $R_B \cdot I$ sets the voltage across R_C, which provides current for both the translator collector and Q2. To minimize thermal distortion, this current should be split about equally between transistors, though to effect the low-end output voltage, Q1 will have to sink the total current.

This CB stage also does not suffer from the Miller effect and is the configuration that can sustain the highest breakdown voltage. With a CE input, the combination is inverting; with a CB input stage, it is not. This is a consideration in feedback amplifier design.

An alternative output stage that allows the low-end voltage to be set by the terminating voltage is a CE stage, as shown below.



In this case, the Q1 dc collector current times R_C sets the voltage across R_{E2}. D1 provides Q2 junction tracking. For both of the above output stages, there is some loss in high-end range due to the input-circuit bias voltages of these stages. This circuit "headroom" voltage subtracts from V_H to set the approximate high-end voltage, and in both cases it can be minimized by about the same amount. In either case at least 1 V will be lost from V_H. By keeping the resistances low on the high-side nodes, not only is headroom minimized, but the circuit is made faster.

To compensate dynamically for the output pole of either the first stage (with time constant of approximately $R_C \cdot C_{bc1}$), R_{E2} can be shunted by a series *RC* ($R >> r_{e2}$), with values chosen to form an equal time constant, as emitter compensation. The CB base can also be capacitively-bypassed to V_H, to keep the base from moving dynamically.

The CE stage provides additional voltage and current gain, whereas the CB provides only voltage gain. Consequently, if the overall amplifier needs additional voltage gain, a CE may be preferred, though a CB is faster.

A third, alternative second stage is limited in low-end output voltage by the first stage, but sometimes that is acceptable. It is a common-collector (CC) or emitter-follower stage, either as a single transistor or, for power amplifiers which require more current gain, a Darlington configuration. No voltage gain is achieved. The output can be returned to a negative supply through a large resistance, to supply a small amount of bias current at quiescence. This keeps the output transistor(s) on and operating linear without dissipating much power.

Bipolar Amplifiers

For bipolar amplifiers, complementary circuitry can be constructed to provide the negative voltage range. How the two halves interact is a design consideration that goes beyond this article. (For much more on this topic, see the volume *High-Performance Amplifiers* in my four-volume CD-book, *Analog Circuit Design*, available at http://www.innovatia.com.) The main interaction occurs at *crossover*, where the circuitry of one polarity eases off while the other takes over. The main design fault to avoid is "shoot-through," where both upper and lower output transistors turn on hard (usually transiently), shorting the positive HV supply to the negative HV supply. This can occur when an NPN of the upper circuit is faster than its counterpart PNP in the lower circuit, and turns on before the PNP is sufficiently throttled back.

Just as 2N3904 and 2N3906 transistors are the run-of-the-mill types for applications with non-critical parameters, the common high-voltage npn devices are: 2N5551 (160 V), MPSA43 (200 V), MPSA42 (300 V), and MPSA44 (400 V); the pnp devices are: 2N5401 (160 V), MPSA93 (200 V), and MPSA92 (300 V). These transistors are quite adequate for amplifiers with bandwidths up to 10 MHz or more. For higher voltages, due to secondary breakdown of BJTs, consider MOSFETs instead.

Feedback and Large-Signal Response

In closing the loop, you might find (by analysis, simulation, or prototype means) that the dynamic response is unsatisfactory and frequency compensation is needed. The simplest strategy to the dynamic aspect of the design is to make the stages as fast as can be done easily, then allow one to be much slower than the rest. This introduces a dominant pole into the loop, which rolls the phase off by 90 degrees long before the additional, high-frequency poles have any effect. Feedback will extend the *closed-loop gain* (which is what matters for amplifier performance) by one plus the loop gain. For precision outputs, the loop gain must be high enough to keep distortion minimal, or to accurately supply the commanded output value of voltage.

Dominant-pole compensation may not work with amplifiers having loads with resonance or other troublesome pole-zero combinations. One approach to load effects is to insert an inverse response network in the loop, to nullify the effect of the load. Small motors often have an electromechanical resonance formed by the load inertia (analogous to C) and the electromagnetic compliance (analogous to L) of the motor, with little damping. In discrete analog designs, a bridge-T notch filter compensates for the resonance.

With a wide voltage range, a large-signal dynamic limitation often occurs, as limited *slew rate.* Slewing is caused by current-limited charging of capacitance in the signal path. One item on the design checklist of high-voltage amplifiers is that biasing (or large-signal dynamic compensation) is set for adequate current.

Another checklist item is that the amplifier performs satisfactorily over the entire dynamic range. If the design is optimized for maximum output, does it still meet specs when operated near zero-scale? It is useful to not only test with a waveform spanning the full-scale range, but to use a small-amplitude waveform offset to 10 %, 25 %, etc. of the range. If the output amplitude changes appreciably when offset over the range, then the amplifier has large-signal non-linearity.

Closure

HV amplifier design requires special attention to transistor voltage breakdown ratings relative to the configuration they are used in, large-signal dynamic response limitations, such as slewing, and the best choice of gain stages within the amplifier, for maximum range while maintaining speed and linearity.

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