 By Ron Mancini

Understanding linear regulators

LINEAR REGULATORS CONVERT unregulated dc voltage to regulated dc voltage. They are good vehicles to use to begin a voltage-regulator study because with them, you can apply the feedback knowledge that I have mentioned in previous columns (**references 1** and **2**). Linear regulators couple excellent regulation characteristics with excellent noise performance and simplicity of use, but their low efficiency and high dropout voltage slightly nullify these advantages.

The series pass transistor, Q_1, changes resistance to keep the output voltage constant when the input voltage, V_{IN}, or the output current changes (**Figure 1**). How does Q_1 accomplish this change? R_1 and R_2 sample the output voltage (V_{OUT}), and you compare the sample to the reference voltage, V_{REF}, in the op-amp circuit. You multiply the difference voltage by the stage gain (approximately $R_F/(R_1||R_2)$) and apply it to the base of the pass transistor. (R_B supplies bias current during start-up.) When the output voltage increases, the sampled voltage increases, and the op amp decreases the pass-transistor base voltage, thereby restoring the original output voltage. The regulator design often eliminates R_F, thus yielding extremely high control-loop gains that lead to high accuracy.

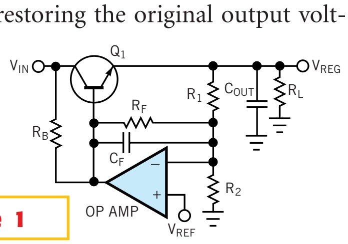

Figure 1

Linear regulators have the best noise and regulation performance.

The linear regulator has excellent performance in all categories except efficiency and dropout voltage. The dropout voltage is $V_{IN}+V_P$ (pass-transistor voltage drop); the regulator can't regulate below this voltage. The following efficiency **equation** assumes that the input ripple voltage is zero and the load current is much greater than the regulator current.

$$E = \frac{V_{OUT}}{V_{IN} + V_P}.$$

The regulator eliminates the tolerance on V_{IN}, but this tolerance, which may be a ripple voltage, causes inefficiency. Furthermore, V_P also contributes to the inefficiency. Linear regulators are most efficient at high output voltages that minimize the input voltage tolerance. When you change the pass transistor from npn to pnp to decrease V_P, efficiency increases, and the dropout voltage decreases. The pnp performance is adequate. However, FETs are popular today because they yield lower dropout voltages. It is wise to use linear regulators when the output voltage is large, the V_{IN} tolerance is small, and V_P is small. Many battery applications fit the second two requirements, so today, engineers widely use linear regulators.

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The regulator output impedance, Z_{OUT}, reacts with C_{OUT} to form a pole in the feedback loop. As the value of C_{OUT} increases, the pole it forms with Z_{OUT} moves toward the low-frequency axis in the s plane. When the pole break frequency becomes low enough, it becomes dominant, and it frequency-compensates the circuit, thereby making the circuit stable. If C_{OUT} has a large equivalent series resistance, R_{ESR}, a pole and zero form in the feedback loop. The pole-and-zero combination is always more stable than a single pole. C_F also forms a pole in the feedback loop. Achieving low error requires a very stiff loop (high loop gain), so you eliminate R_F and enlarge $R_1||R_2$ to achieve a dominant pole with C_F. The dominant-pole compensation technique always yields slow response to an error, so you need C_{OUT} to source or sink current to minimize the error. Notice, the regulator can only source current, so you may connect a diode across the pass transistor (anode at the output) to dump load currents into V_{IN} when inductive loads discharge into V_{OUT}.

The regulator can't be more stable than the reference voltage, so you must select the reference with care. Any noise that the reference generates amplifies at the output, so you want low-noise stable references. Obtaining adequate reference-noise performance often requires filtering. The output voltage from a linear regulator is the purest dc you can obtain; thus, linear regulators are desirable for powering circuits that have low signal voltages.□

REFERENCES

1. Mancini, Ron, "Feedback made simple," *EDN*, Jan 15, 1998, pg 24.
2. Mancini, Ron, "Feedback made simple—continued," *EDN*, Feb 16, 1998, pg 26.

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