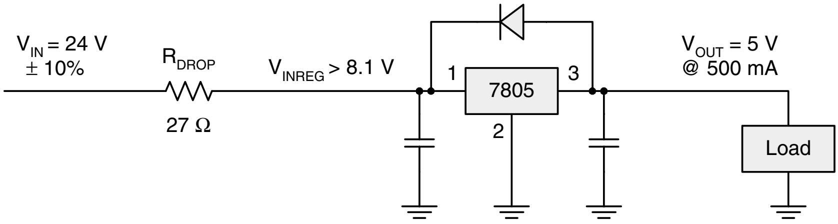

FIGURE 17.12 Shifting power dissipation to a resistor.

27-Ω dropping resistor is inserted before the regulator. The dropping resistor is sized based on the load current, the minimum input voltage, and the regulator's dropout voltage. Working with a conservative dropout voltage of 3 V and a minimum input level of 21.6 V, the resistor must drop a maximum of 13.6 V at 500 mA. The closest standard resistor value, 27 Ω, yields a drop of 13.5 V at maximum load with a power dissipation of 6.75 W. Finding a power resistor that can safely dissipate about 7 W is not a problem. This reduces the power dissipated by the LM7805 to just 3.1 V × 500 mA ≈ 1.6 W. However, the worst-case power dissipation occurs when the input is at its maximum of 26.4 V. The increased differential of 7.9 V results in a power dissipation of approximately 4 W, as expected. We did not save any power, but the regulator's share of the power has been decreased by more than 60 percent, and it is much easier to cool 4 W than 11 W.

Linear regulators provide the easiest and least troublesome manner by which to provide a digital circuit with clean power. They work without causing problems as long as proper thermal analysis is performed and they are kept from overheating. The main reason for not using a linear regulator is its inefficiency, particularly at higher input/output voltage differentials. It is quite convenient to use a linear regulator to derive 3.3 V from 5 V at currents under 1 A. Power dissipation becomes a bigger problem when dealing with several amps. When tens of amps are required, the thermal problem becomes critical, and a more efficient alternative must often be found in the form of a switching regulator.

17.6 SWITCHING REGULATORS

An ideal power regulator would achieve 100 percent efficiency by drawing only as much power from the source as required by the load. Assuming that the input and output voltages are unequal, the ideal regulator would convert a supply current into a different load current to maintain constant power under two different voltages. A linear regulator is nonideal, because it is inherently dissipative—it simply discards the excess power not required by the load, because it cannot convert an input current into an unequal output current. *Switching regulators* approach the ideal much more closely, because they are able to perform the current conversion process. Finite power losses in the switching regulator's components are what cause it to deviate from ideal efficiency. Depending on the input/output characteristics and the circuit used, efficiencies between 80 and 95 percent are realistically achievable.

Switching regulators operate by alternately applying and removing input power from a passive LC circuit. Figure 17.13 shows a simplified conceptual *step-down* regulator circuit, often called a *buck* regulator. The switching element alternately connects the inductor to the input and ground. When the switch selects the input, current flows through the inductor and charges the capacitor. During this time, the inductor develops a magnetic field resulting from the current passing through it. An inductor resists changes in current, because a current change disrupts its magnetic field. Whereas a

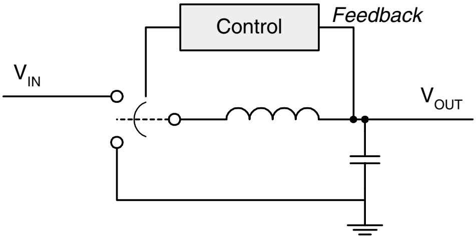

FIGURE 17.13 Conceptual step-down regulator.

capacitor opposes voltage changes by sinking or sourcing current, the inductor changes its voltage to maintain a constant current flow. When the switch selects ground, the inductor instantly flips its voltage so that it can continue supplying current to the capacitor. The inductor holds a finite amount of energy that must be quickly replenished by switching back to the input voltage. The role of the feedback and control circuit is to continuously modify the switching frequency and/or duty-cycle to maintain a fixed output voltage.

There are varying designs for switching circuits. Two common topologies often seen today are shown in Fig. 17.14. Most modern switching regulators employ power MOSFETs because of their low R_{DS}. Prior to the availability of power FETs, power BJTs were used as switches, and their finite $V_{CE(SAT)}$ resulted in higher losses than seen with modern FETs. When a single transistor is used as the switch, a diode serves as the ground shorting element, or rectifier. The diode is reverse biased when the transistor is conducting, and it becomes forward biased after the switching event causes the inductor's voltage to flip. The inductor changes its voltage to maintain a constant current flow, which causes its switch-side voltage to suddenly drop, and the diode clamps this dropping voltage to near ground. Substantial current flows through the diode and motivates the selection of a low forward-voltage Schottky diode (note the S-curve symbology for a Schottky diode). Power loss in this diode is a major source of switching regulator inefficiency. This has given rise to the dual-transistor switch circuit that replaces the diode with a FET as the main rectification element. When a transistor is used in this manner as a rectifier, the common industry term is *synchronous rectification*. The FET's low R_{DS} makes it a superior solution to the fixed voltage drop of the Schottky diode. However, a diode is still present to serve as a rectifier during the short but finite turn-on time of the bottom FET.

Minimal power loss in the switching transistors is a key attribute that enables high-efficiency switching regulators. A switch transistor is ideally either on or off. When off, the transistor dissipates no power. When on, there is minimum voltage drop across the transistor and, hence, minimal power

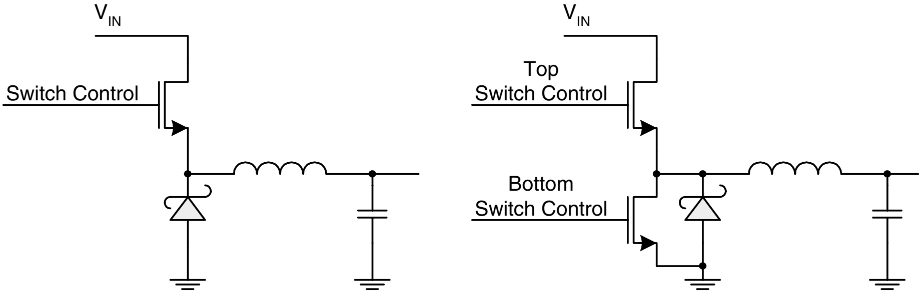

FIGURE 17.14 Single and dual FET switching circuits.