dissipation. Switching control circuits seek to turn transistors on and off as rapidly as possible to minimize the time spent in a region of higher voltage and current. The drive strength required to rapidly switch a large FET can be substantial, because a larger gate results in higher capacitance that must be charged to change the transistor's state. In reality, the finite on-off FET switching times are another significant source of power loss.

Aside from their high efficiency, switchers are extremely flexible, because they can do more than regulate down. *Step-up* regulators, often called *boost* regulators, can convert a lower input voltage into a higher output voltage. *Inverting* regulators can generate negative output voltages from a positive input. Switchers can also be designed for *buck-boost* operation, whereby an output can be generated from an input that is near the output level. This is a very useful feature for some applications, because it bypasses the problem of dropout voltage. Battery-powered portable devices commonly use step-up or buck-boost regulators because of the cost and size advantage of using fewer battery cells. Without a switcher, such a device would require more cells to meet the minimum dropout voltage of a linear regulator.

Each type of switching regulator has a different topology. Most contain FETs, diodes, inductors, and capacitors. Some low-current switchers are now available that do not need inductors. A complete presentation of switching power supply circuit design is unnecessary in the context of most digital systems, because semiconductor manufacturers have done an excellent job of producing integrated switching regulator ICs that are easy to use by following recommended circuit and connection diagrams. Perhaps the easiest way to use a switching regulator is to purchase an off-the-shelf module that already has the full circuit assembled and tested. Companies including Datel, Texas Instruments, and Vicor offer these ready-to-use modules.

More flexibility (and more work!) is possible when discrete ICs are used. Linear Technology, Maxim, and National Semiconductor offer wide varieties of switching regulator controller ICs that require the addition of FETs, inductors, capacitors, diodes, and resistors. (Some low-power regulator ICs incorporate the FET switch on-chip to reduce circuit complexity.) These circuits can be fully customized for individual applications, and manufacturers supply detailed example circuits and documentation to assist in the design effort. As with any semicustom design, more flexibility is possible in terms of the circuit layout to squeeze into small spaces. The trade-off is increased design effort to ensure that numerous discrete components operate properly.

Whatever implementation path is chosen, the incorporation of switching regulators into a system brings with it a set of issues that are either not present or not as potentially troublesome when using linear regulators. A switching regulator introduces noise and ripple because of its high-current on-off operation. Many switcher design issues revolve around minimizing this noise and ripple. The selection of the inductor and capacitors is very important. An IC vendor will usually recommend a particular inductor for a given switching frequency and output current. Because power inductors can get quite large, a current trend is to use smaller inductors at higher switching frequencies with the consequence of introducing higher-frequency noise into the system. If the high-frequency noise cannot be adequately filtered, a larger inductor may be used at a lower frequency.

Attenuating ripple and noise generated by the switching regulator is accomplished in large part by using high-quality capacitors with extremely low equivalent series resistance, or ESR. The capacitors' ESR must be minimized because of the high current spikes sent through the inductor by the switching element. Each current spike will develop a voltage across the capacitor's finite ESR. Higher resistance means higher voltage ripple. Ideally, ceramic surface-mount capacitors would be used because of their excellent high-frequency characteristics. Some switchers do use these capacitors, but their use is limited, because ceramics do not provide very high capacitances. High-power switchers require large capacitors rated at hundreds or thousands of microfarads. Tantalum and aluminum electrolytic capacitors are commonly used in switcher circuits. Normal electrolytics do not have adequate ESR for many switching applications, but manufacturers such as AVX, NIC, Nichicon, Panasonic, Sanyo, and Vishay have developed special-purpose lines of low-ESR electrolytic capacitors. Typical ESR for these capacitors is from 10 to 100 mΩ.

## 17.7 POWER DISTRIBUTION

Power regulation and distribution circuits inherently handle significant quantities of power in relatively compact volumes and are designed to provide power with minimal source impedance, making safety a prime concern. Minimal source impedance is highly desirable when evaluating a regulator's ability to supply high current at constant voltage. This characteristic also means that there is nothing preventing a short circuit or overload condition from drawing power beyond the circuit's specifications. When high power density and low source impedance are brought together, there is the potential for serious injury and damage if a component were to fail and cause a short circuit.

Reliability of power distribution is directly related to safety, because an unreliable circuit may fail in an unsafe manner. Yet even if the failure causes no damage, a failure is still quite undesirable. The reliability of a circuit is influenced by how heavily loaded its individual components are. Operating components at higher thermal loads (higher temperatures) degrades their longevity. Operating components at greater fractions of their rated current, voltage, and power also reduces their life span. Conservative designs use power components that are rated well in excess of their actual operating load.

Many electrical safety codes and standards have been adopted over time to minimize the adverse consequences of power circuit failures. In the commercial and residential AC wiring context, there are strict regulations requiring insulated connections, minimum wire gauge, maximum wire length, and fuses. The basic idea is to first reduce the chance of failure by employing conservative design practices. Adequate insulation reduces the likelihood of shorting. Limits on wiring ensure that the conductors can carry the desired load. Second, the inevitable failure's effects must be minimized. Engineering in general, but power engineering in particular, requires the anticipation of failure regardless of how unlikely that failure is. Murphy's law is a constant across all disciplines. Fuses are the main failure-handling mechanism in power distribution. A fuse is rated for a certain current and will blow when that current rating is exceeded. In the unlikely event of a short circuit, the fuse blows, and all power is cut off to that branch of the power distribution system. Fuses are the last line of defense, because they are simple, passive devices that deal with the problem in a quick and decisive manner.

Figure 17.15 shows a logical view of a power distribution system where the AC-to-DC rectification and preregulation functions are separated from the final DC-to-DC regulator that directly powers the load. Some power systems combine these elements into a single module, and others use a distributed approach as shown here. The AC-to-DC and DC-to-DC functions are logically separate

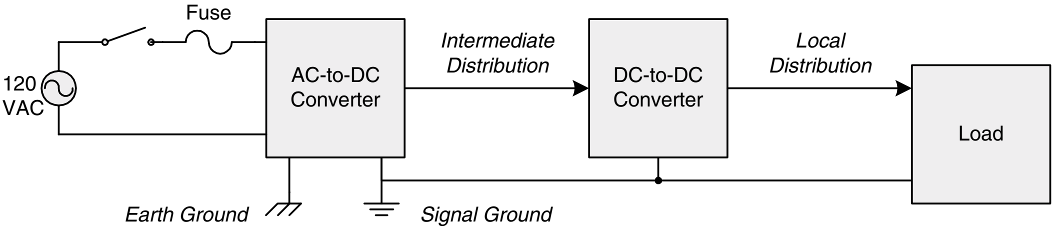

**FIGURE 17.15** Overall power distribution.