

BY PAUL RAKO • TECHNICAL EDITOR

POWER—FROM LINEAR TO DIGITAL—COVERS A RANGE OF DESIGN CHOICES. THIS BRIEF OVERVIEW PRESENTS DESIGNERS WITH SOME OF THE ALTERNATIVES AND PROBLEMS THAT WILL ARISE.

CREATING THE POWER SUBSYSTEM IN MODERN DESIGN

Power electronics range from the simplest to the most complex subsystems in modern products. This fact is not surprising because the applications also range from simple to complex. At the simplest, a power supply can be a big zener diode, such as those that find use in submarine cable-repeater pods. These pods need the ultimate in reliability, and a resistor-plus-diode approach is the simplest and hence most reliable. The zener dissipates a significant amount of heat, but the temperature of the ocean floor easily removes that heat. Slightly up the complexity ladder are linear regulators—popular and useful parts. The LM317



is the most frequently downloaded data sheet at National Semiconductor's Web site. A linear regulator operates like a valve. It resists the current in the circuit to ensure that voltage stays constant. Remember that the word "transistor" derives from the combination of the words "transconductance" and "varistor" (**Reference 1**). The transistor in a linear regulator pinches off the current to control voltage—hence, it provides transconductance. In this operation, it serves as a variable resistance, or varistor. Conventional linear regulators have NPN-pass elements. Low-dropout regulators use PNP transistors.

A more complex regulator is the charge pump. It uses several transistors as switches, not linear elements. These switches transfer charge to a capacitor and then change the connections so that the capacitor doubles or inverts the original voltage you impress upon it.

You realize a large jump in complexity when you move to switching regulators. These circuits have high-frequency magnetics, a control loop, and at least one transistor acting as a switch. You can buy the entire regulator as brick from Vicor or Tyco, or you can roll your own and build the regulator from parts. Buck, boost, inverting, isolated, SEPIC (single-ended primary-inductance converter), and Cuk (pronounced "chook") are all types of switching regulators.

All of these power circuits convert one dc voltage to another dc voltage. A significant number of designs use transformers to change ac voltage or circuits that convert ac to dc for subsequent dc-to-dc conversion. One of the most elegant ac-to-dc-conversion circuits, the PFC (power-factor-correction) circuit, uses a boost-converter topology to ensure that the input current to a converter is proportional to the input voltage, unlike the sharp spikes of input current that occur in conventional ac-to-dc circuits.

A new term in the power world is "digital power" (**Reference 2**). It can mean anything from simply being able to use a digital input to shut down the regulator, to having digital communication to the chip for monitoring and control of the analog-PWM process, to having a DSP close the loop and directly control the pass element with a PWM signal.

Starting with the basics, a linear regulator uses a transistor to step down a dc

AT A GLANCE

Power subsystems can be linear, switching, charge pump, ac/dc, digitally managed, or digitally controlled.

Linear supplies face thermal issues.

Charge pumps entail noise injection.

Switching supplies must deal with stability, noise, and thermal problems.

Digitally managed and digitally controlled power often requires a software effort right before product release.

voltage. A conventional linear regulator, such as the LM317, uses an NPN transistor as the restriction. Because of the 0.6V drop in the base-emitter junction, these regulators need a significant amount of head room to operate. Engineers often mistakenly assume that the output voltage is in regulation even when the part is maintaining less than the recommended dropout voltage. The part may provide the right voltage but does not meet several ac and thermal specs. Engineers lived with the large head-room requirements of linear regulators until the early 1980s, when US automobile manufacturers approached the semiconductor industry with the need for a low-dropout linear regulator. The regulators designed for low head room, such as the LM2936, used PNP pass transistors. This approach allowed the regulated circuit to stay in regulation even if the battery voltage sagged

to 8V during the car's cranking period while starting. According to Al Kelsch, product-definition manager at National Semiconductor, as the dropout voltage approached zero, a "caret," or small spike of input current, would arise because the base of the pass transistor was at maximum turn-on. Although the IC designer spent a lot of time designing a base-drive circuit that would limit the current and eliminate the caret and still provide transient response and other specs, customers needed that little caret to sense when the regulator dropped out; they could then turn off the entire circuit. In other words, customers viewed as a feature what the designer perceived as a bug.

The overriding problem with linear regulators is heat. Because the regulator has both significant voltage and significant current running through the pass transistor, it dissipates a lot of power. Most linear regulators have a thermal shutdown, which may save the part from destruction, but it also makes the circuit unusable if the shutdown happens in any operating situation.

Another design issue with linear regulators also applies to most power supplies. You must assume that any electrolytic capacitors will short-circuit at some point during the lifetime of a product. If a short circuit occurs, you must ensure that the regulator and board do not burn or cause other damage. You must also provide a fuse or a fusible pc trace on the input electrolytic capacitors and on any tantalum capacitors. Even if the product's wall wart cannot provide enough current

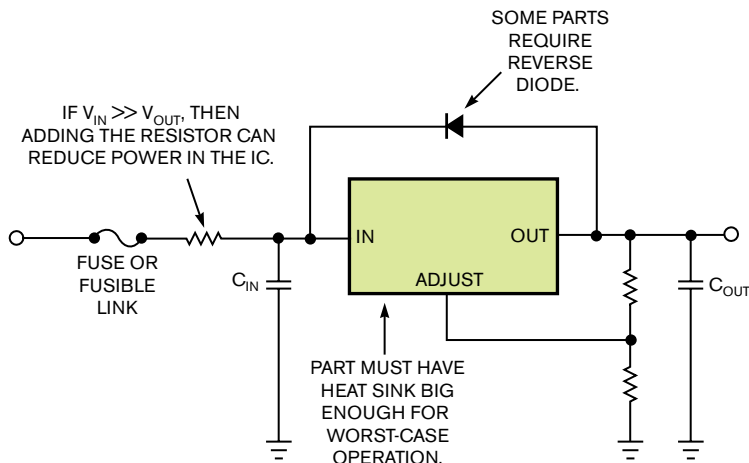


Figure 1 Linear supply problems are heat, capacitor shorting, and damage to the part when reverse currents flow inside the IC.



to start a fire, a diligent engineer must provide for the situation in which a user uses a larger or incorrect wall wart to power a product (Figure 1).

CHARGE PUMPS

Another type of dc/dc converter, the charge pump, can invert, double, or triple an input voltage by switching a capacitor across the input voltage to charge the capacitor. You can then switch that capacitor to sit on top of the input voltage, forming a doubler. Alternatively, you can connect the positive terminal of the capacitor to the input common, creating a voltage inverter. The classic charge pump is Intersil's ICL7660, which the company introduced in the 1980s. Another such device, Catalyst Semiconductor's CAT3636, employs a novel method of achieving noninteger voltage steps of 1, 1.33, 1.5, and 2V. This approach allows efficiency as high as 92% in handheld-system applications. This efficiency compares with that of conventional inductive boost converters, especially in view of the fact that many manufacturers specify efficiency numbers for those converters based on unreasonably large inductance.

Because the capacitor inherently limits the amount of current that the part can deliver, thermal problems are rare in

charge pumps. They do have some drawbacks, however, including poor voltage regulation. The output changes with the input unless you employ a linear postregulator. Maxim has addressed this issue with a line of postregulator charge pumps. The switching frequency and noise of a charge pump are far less problematic than the noise from a switching converter, but the noise may still enter the signal chain.

Another type of regulator, the switching regulator, uses a transistor switch with an inductor or transformer to change a dc-input voltage. Figure 2a shows a buck-switching regulator that steps down a voltage and that operates analogously to a water wheel (Figure 2b). The device's rate of rotation is analogous to the current following through the inductor. Just like an inductor, the water wheel cannot instantaneously stop or start. The figure may give some insight about why engineers often refer to the diode as "freewheeling." When the valve turns off, the inertia of the water wheel creates a powerful suction. The wheel needs water to keep rotating, and the check valve provides this function.

A boost converter employs the same water-wheel analogy (Figure 3). Many engineers have trouble with magnetic

circuits because their high reactance means that the current does not track the voltage as it does in a resistor. An intuitive understanding of the buck and boost converters allows you to understand the more complicated architectures, such as Cuk, boost-buck, and SEPIC. Converters can also use transformers to create an isolated output (Figure 4). Flyback converters, which differ from forward converters only in the polarity of the output diode, use a transformer as a choke. They store energy in the magnetic field when the switch is closed and as current increases in the primary. When the switch opens, the energy in the magnetic field discharges through the secondary. Designers favor flyback converters for their low cost and their ability to make multiple outputs that all track each other reasonably well.

Most engineers have difficulty designing robust switching converters. The first problem is stability. Stabilizing their complex control loops can be a daunting task because many converters require a ripple in the output voltage to work properly. Others exhibit subharmonic oscillations, and you must inject a ramp signal into the reference. When large-value ceramic capacitors became affordable, many engineers substituted them

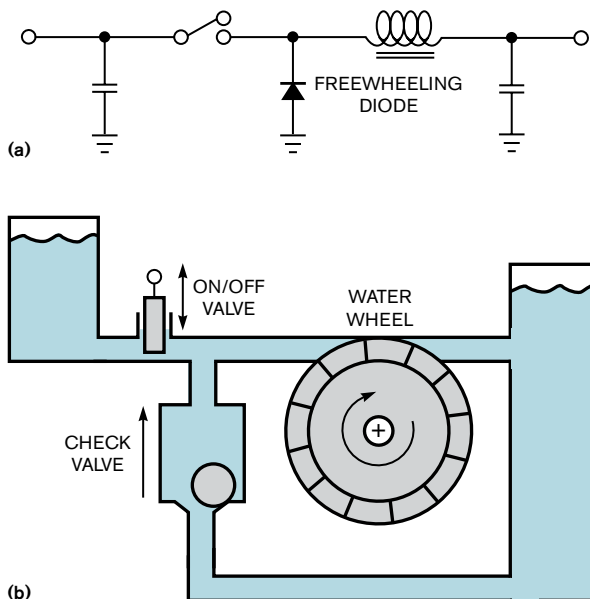


Figure 2 A buck regulator steps down the input voltage (a), and you can make a water-wheel equivalent (b).

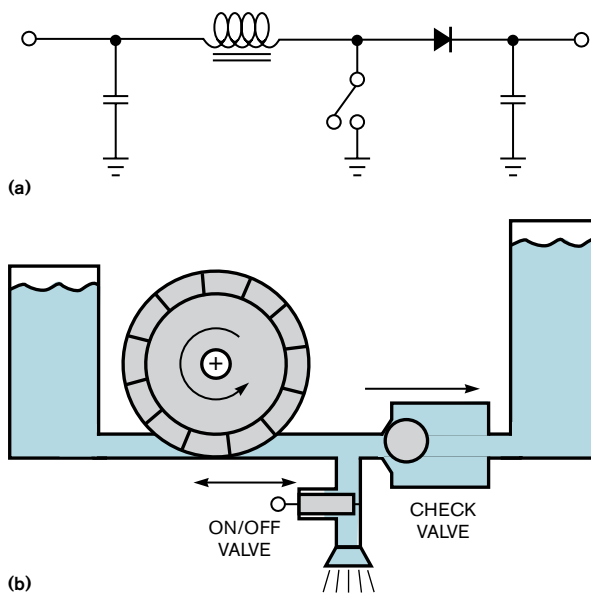


Figure 3 A boost regulator steps up its input voltage to a higher level (a), and a water-wheel equivalent provides insight to the circuit (b).



for electrolytic output capacitors. Ceramic capacitors have such low ESR (equivalent-series resistance) that they have essentially no ripple voltage, causing oscillation. The ripple voltage itself may violate design requirements, such as when powering analog circuits. This problem requires postregulation or the use of extra inductive damping.

Another common problem, noise, can radiate back into the input or output power lines or radiate into space as electromagnetic radiation. The worst issue with this problem is that a designer may not notice it until sending the product for FCC (Federal Communications Commission) and CE (Conformité Européenne) testing just before production. Designers can use various techniques to shield this noise from the world and the rest of the system. It is better to not generate the noise in the first place than to later attempt to shield it in tens or hundreds of end-user applications.

As with linear regulators, thermal issues can also be problems in switching converters. Most buck regulators generate more heat in the freewheeling diode than in the FET. A thermal plot from National Semiconductor's Webench online-design tool shows that diode D_1 is the hottest component on the board and is heating the IC it abuts (Figure 5). To reduce the heat that freewheeling diodes generate, synchronous buck regulators replace the diode with a second out-of-phase FET.

Most of the above problems are traceable to an inferior pc-board layout. Several articles are available that discuss the pitfalls of laying out a good switching regulator (references 3 and 4). Engineers should always take advantage of the applications-engineering staff of the companies that make the regulator IC. They can avoid an enormous amount of frustration and chaos if the applications engineers can review your design and layout before you commit the board to fabrication.

OFFLINE REGULATORS

This article has so far discussed only dc/dc converters. Another class of converters creates dc power from ac power. The ac power most commonly comes from residential ac-power lines; the converters are thus offline supplies (Reference 5). Other designs use an isolated topology to

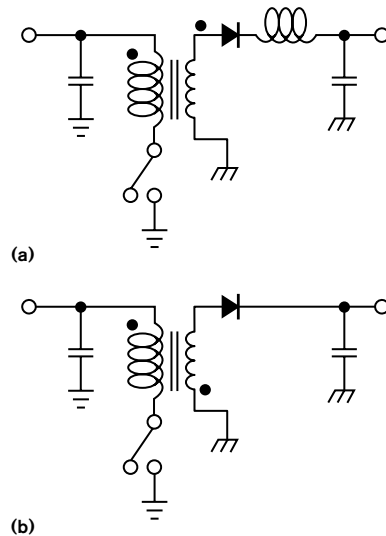


Figure 4 Common isolated converters include the forward (a) and the flyback devices (b).

create one or more dc supplies from raw dc power from the classic rectifier circuit. Allegro, On, STMicro, Power Integrations, and the Unitrode division of Texas Instruments make these types of devices.

Offline-supply problems include inrush currents and harmonic currents. Inrush current is the large flow of current necessary for charging up the input capacitors at the moment of closing the input switch. This current can stress the rectifier diodes and cause early capacitor failure. Approaches to correcting this problem include the use of NTC (negative-temperature-coefficient) devices in series with the inputs (Reference 6). These devices offer a high resistance when they are cold. As the input current runs into the capacitor, the devices heat up, and the resistance decreases. Drawbacks can be the 190°C operating temperature as well as sensitivity to ambient temperature.

The second problem with offline supplies is that the input capacitors draw in large spikes of current. These spikes top off at every line cycle. Using PFC, which is mandatory on supplies sold in Europe, can reduce these spikes. Remember to fuse the electrolytic capacitors. Failing UL (Underwriters Laboratories) fire testing just before production is as calamitous as failing FCC and CE EMI/RFI (electromagnetic-interference/radio-fre-

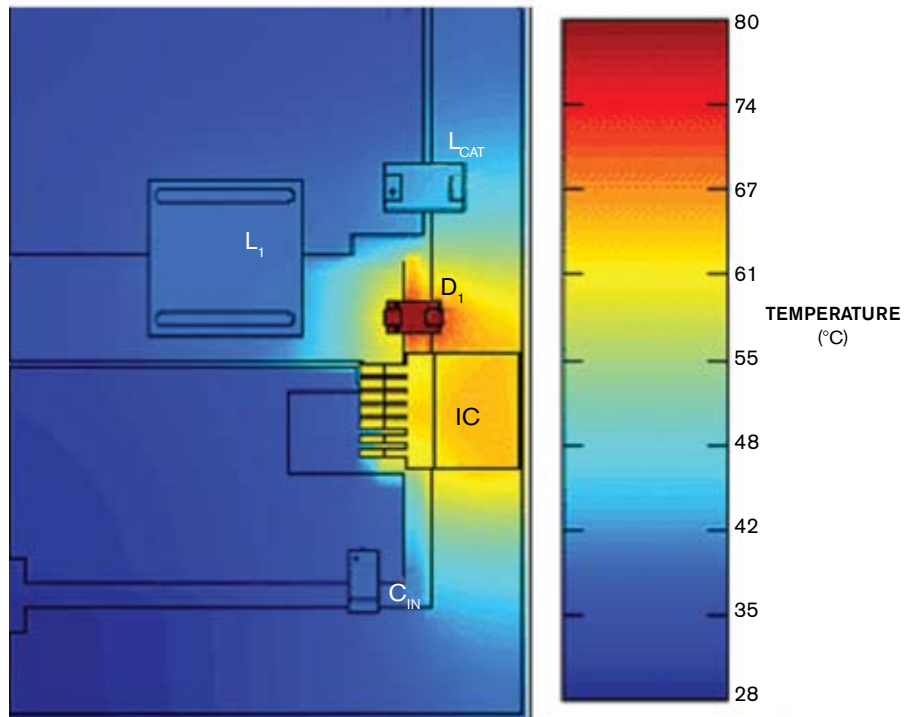


Figure 5 A thermal map shows that the freewheeling diode D_1 is the hottest component in the circuit (courtesy National Semiconductor).



quency-interference) testing.

Another common problem with off-line regulators using a switching IC is the quiescent current of the start-up circuit. You must provide 5 to 10V to the chip before any oscillation and regulation can begin. So, you must often use a large power resistor to feed this voltage to the chip. If you place the resistor across the 170V or higher dc bus to the 5 or 10V IC power rail, significant power dissipation will occur. Designers can in these cases use 500V Supertex depletion-mode FETs, but that option may be infeasible for low-cost supplies. Some vendors, such as Power Integrations, have developed alternative architectures to deal with this problem. "Solutions that use an integrated power transistor can derive the power for the control section by using the high-voltage MOSFET as a potential divider and tapping off a small amount of current at low voltage," says Doug Bailey, the company's vice president of marketing. "Power Integrations uses this approach in all of its switching ICs, and it works very well."

Digitally managed or controlled power uses a conventional analog PWM loop but hooks in substantial digital control, beyond the ubiquitous digital-shutdown pins on most controllers (**Figure 6**). Digitally managed power ICs first found use in battery-charger ICs. Older chemistries, such as lead-acid batteries, frequently used a voltage-regulator IC set to provide 2.3 to 2.36V per cell, depending on whether the application can tolerate higher charging voltages. Even these simple chargers often add ambient-temperature sensing, time limiters, or cell-temperature sensing to adjust the charge voltage. Nickel-metal-hydride and, to a greater extent, lithium-ion chemistries require even more digital supervision and manipulation. The system designer may want to terminate the charge cycle based on a rise in temperature or a rise in voltage. You should not start full-power charging if the battery is dead. If this situation occurs, the charger IC must "burp" a little current into and monitor the cells until the voltage becomes high enough to accept full-power charging. If the battery has been charging for several hours and still has not achieved termination, the IC should end the cycle. Ambient-temperature faults and many other variables may

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also be pertinent. "We no longer think of a battery-charger IC as a PWM circuit with some logic," says Mary Kao, an application engineer at National Semiconductor. "We look at it now as a microcontroller with an analog-PWM section."

Once battery-charger ICs paved the way, many other applications demanded a large portion of digital control over analog PWM loops. For example, Xilinx FPGAs require strict power sequencing and control. One vendor, Cradle, makes a multicore-DSP IC. Because it is a 0.13-micron CMOS part and uses DDR SDRAM, the power-system design was

challenging. The requirements include 3.3V for I/O, 1.2V for the core, 2.5V for the DDR-SDRAM I/O, 1.25 sink source for the DDR-SDRAM-impedance voltage, a DRAM voltage reference, and 1.8V for another IC. Cradle engineers Tapeng Huang and Craig Calder worked with Mike Cheong at Intersil to redesign five separate power outputs using a single multichannel controller. They have two dc/dc controllers, two dedicated DDR outputs, and two uncommitted low-dropout regulators. In a more familiar area, most PC enthusiasts know that the supply voltage to the processor and memory is under digital control. Hand-held devices may have complex control requirements to conserve battery power and extend runtimes.

Digital power uses a DSP rather than an analog PWM loop to do the math to keep the loop stable (**Figure 7**). This

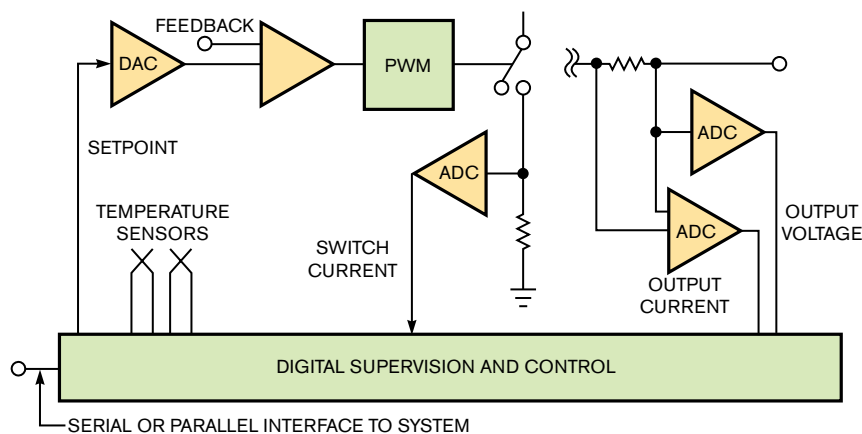


Figure 6 Digitally managed power uses a conventional analog-control loop but has extensive digital circuitry to perform monitoring and control functions.

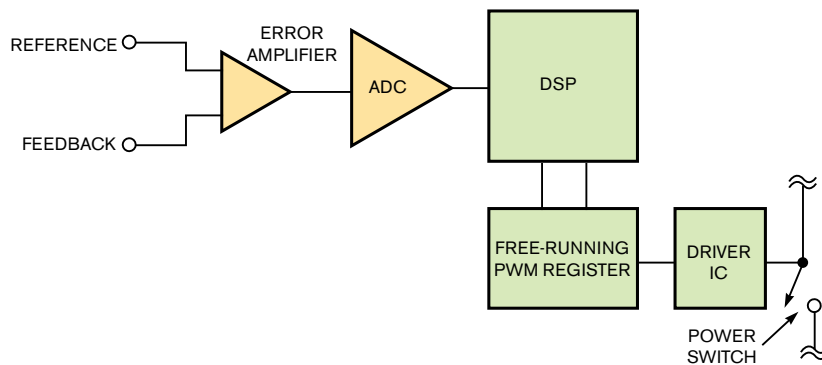


Figure 7 Digital power replaces the analog-control loop with a DSP or a digital-state machine.

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approach can provide flexibility in the loop compensation, but that flexibility comes at a price. Dave Mathis, a principal at Elandesigns points out: "If you are going to change the compensation, you have to be sensing something to base that change on. With acquisition times and error conditions, that is just asking for trouble." Indeed, experienced control-system engineers know that well-behaved systems usually have a single dominant pole. Nevertheless, Texas Instruments, Silicon Labs, and Primarion all make digital-power devices. Primarion has published articles stating that all power will be digital in the future and that analog engineers are only protecting their turf when they resist implementing digital power (Reference 7). Primarion does not use a DSP to manage the control loop. Rather, the company employs a free-running state machine that uses far less power than a DSP. Still the control is in a digital loop rather than an analog PWM loop. Steven Bakota, manager of digital power at Texas Instruments, points out: "Digital power is nothing new. TI has been selling digital power for 10 years ... in the form of libraries to use with standard DSPs. The difference now is that we have our Fusion line of custom-built parts and a software-development environment to ease the implementation of the design."

Diligent power-supply designers must remember that 60,000 transistors in a DSP provide the control loop of a digital-power system, whereas an analog approach requires only about 100 transistors. Digital-power aficionados also brag about quiescent-power consumption of

7 mA. That figure may be acceptable in a blade server that operates from a wall outlet, but no battery-operated or portable product could afford that much power loss. An analog approach, in contrast, can operate at less than 1 mA. Designers should also evaluate a momentary power loss on the system. If the DSP has to re-initialize and run user-written code after a supply transient, that may make the supply unsuitable for some applications. A final caveat is that managers have to be willing to put a complex software-development effort right at the end of a product's design cycle, which is typically when the power subsystem is designed. Managers should not be lulled by promises of triviality in the design. If the design was trivial, an analog PWM part could do it at lower cost and less quiescent current. Make sure that a digitally managed system is not more appropriate than full DSP digital control of the loop. **EDN**

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