IN OUR LAST EDITION, WE EXAMINED the basics of switching regulator power supplies. Now we'll dive into some real-world applications. We'll examine the 3524/5/7 and 3842 IC families in detail, summarize others, and show some typical circuits. In the process we'll study how to select components for those circuits and learn more about how switching regulator IC's are protected against such problems as startup current surges, undervoltage, and overload. We'll finish up with some basic troubleshooting hints.

Let's first start off with an explanation of the standard nomenclature used in naming the IC's we will discuss in this article. The first digit "1" indicates full military temperature range of −55 to 150°C, "2" indicates an industrial temperature range of −25 to 85°C, and "3" is a commercial temperature range of 0 to 70°C. Hereafter, we will refer only to the commercial version IC's, with prefix "3." Keep in mind that all those IC's are also available in military and industrial versions. A suffix of "A," "B," or "C" indicates an enhanced version of the IC, which we will discuss in more detail later in this article.

Manufacturers may use many different prefixes, some of which include
SG—Signetics, SGS-Thomson, Motorola, and Linear Technology.
CS—Cherry Semiconductor.
XR—Exar.
CA—GE-RCA.
IC—IPS.
LTSG—Linear Technology.
LM—National Semiconductor.
UC—Unitrode, Motorola, Linear Technology, and Signetics.
UD—SGS-Thomson.
IP—IPS.
LAS—Lambda.

The SG3524/5/6/7 IC

Figure 1 shows the internal circuit of the switching regulator IC SG3524. In that circuit, the oscillator produces both ramp and pulse outputs. Ignoring the current limit (CL) and shutdown circuits for the moment, the comparator's output goes high when the ramp exceeds the output of the error amplifier. The NOR gates then go low, turning the output transistors off.

Each NOR gate can be high only when its three inputs are low. The oscillator output toggles the flip-flop, enabling one gate, and then the other to respond to the comparator. That action gates one transistor on at a time, providing push-pull operation. The selected transistor turns on at the start of each cycle, and turns off as soon 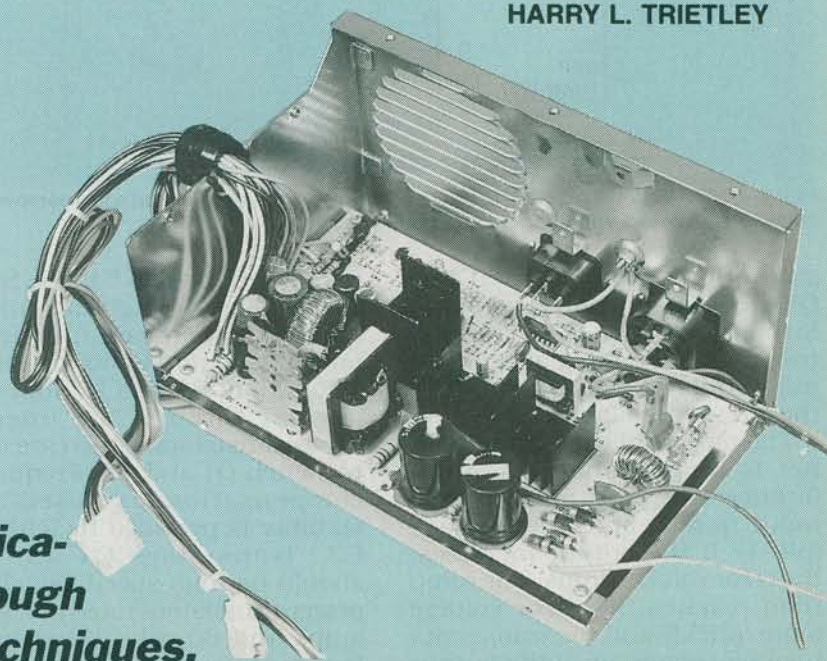as the ramp exceeds the error signal. At the end of each cycle, the oscillator pulse momentarily forces both gates low, protecting against the possibility of both transistors being on at the same time.

The current-limit amplifier protects against current overloads. Its output is an open-collector type—open-circuit when high, pull-down to ground when low. The current-limit amplifier and the shutdown transistor can be used to force the comparator output high, shutting down both transistors.

Figure 2 shows the SG3524 in a simple DC-DC converter. The oscillator frequency of about 60 kHz is set by R5 and C2. (The flip-flop divides the push-pull output frequency to 30 kHz.) The current-limit amplifier goes low when its input exceeds 0.2 volts, limiting R11's current to 2 amps in case of overload or transformer

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SWITCHING
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We'll take an in-depth look at two switching regulator IC families, with some applications, and guide you through basic troubleshooting techniques.
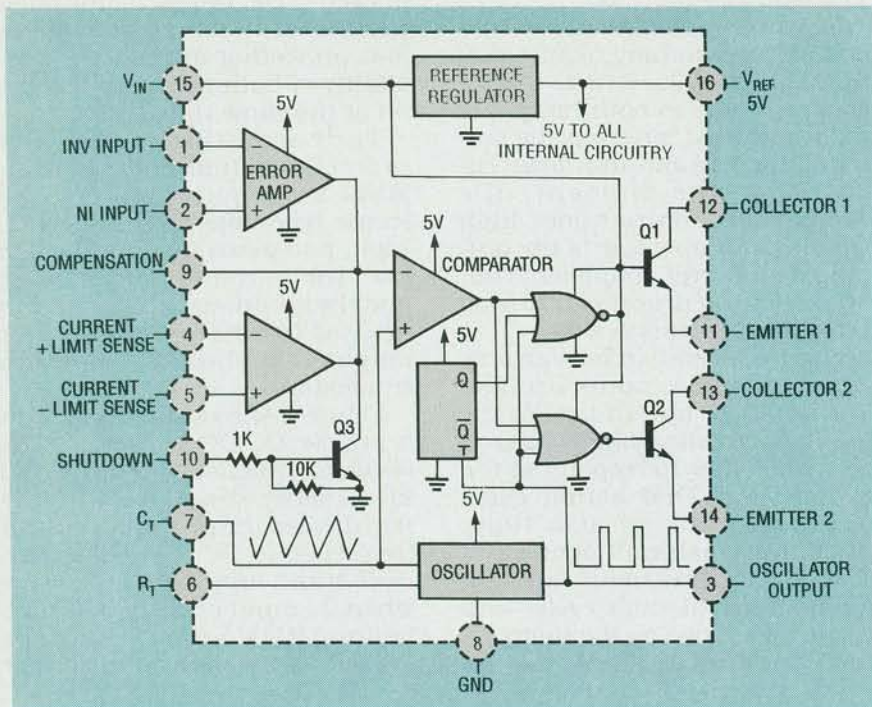
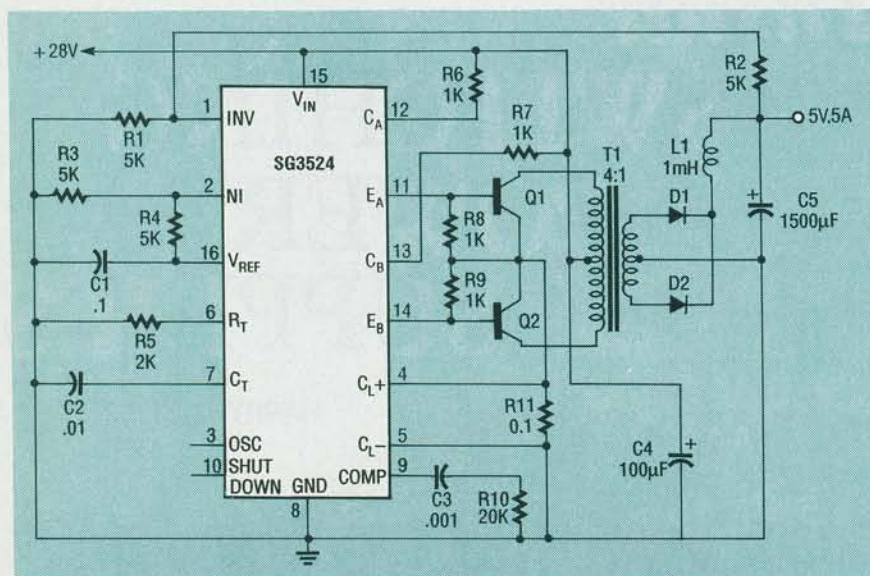**FIG. 1—INTERNAL BLOCK DIAGRAM of the SG3524 switching regulator IC.**

FIG. 2—THE SG3524, TWO SWITCHING transistors, a transformer and a few components create a complete 5-volt push-pull switching regulator.

saturation. Transistors Q1 and Q2 are used for switching transformer current. (The on-chip transistors are rated at only 100 mA.) Supply pulses produced by the circuit are filtered by C4.

The output of the error amplifier is proportional to the difference between the reference input (pin 2) and the feedback (pin 1). If the output increases, the error voltage drops. The ramp then reaches the error voltage more quickly and the transistors turn off sooner, until the output

is reduced back to 5 volts. Since the feedback voltage and ground are directly connected, input-to-output isolation is not provided.

Resistors R6 and R7 limit the current through the internal drive transistors, which are used to switch Q1 and Q2. Frequency compensation for closed-loop stability is provided by R10 and C3. Transistors Q1 and Q2 should be high-speed switching power transistors rated at least 5 amps and 60 volts. Shottky or fast-recovery diodes should be

used for D1 and D2. Because the output is balanced, the transformer core does not need to be gapped, a small ferrite core will do.

At high frequencies, the equivalent series resistance (ESR) of filter capacitor C5 is higher than its capacitive impedance. Low series-resistance electrolytics should be used, preferably capacitors designed specifically for switching supplies.

The enhanced SG3524A

Figure 3 shows the enhanced version SG3524A, which is pin-compatible and interchangeable with the non-A version. The enhanced version adds an under-voltage lockout circuit which disables the regulator until its input rises above 8 volts. That holds current drain to standby levels during turn-on, guarding against problems during startup, surges, and brownouts. A pulse-width modulator latch is also added, which eliminates multiple pulsing in noisy environments. Set by the comparator and reset by the clock pulse, it can switch only once per comparison cycle.

Further protection is provided by thermal protection circuitry (not shown). Performance specifications also are improved—the 5-volt reference is trimmed more closely ($\pm 1\%$) and the error amplifier's output can swing up to the 5-volt rail.

Let's look at one more member of this family, and an application. Figure 4 shows the workings of the SG3525A/7A. The 3525A and 3527A differ only in their output logic; the 3525A is low when off, while the 3527A is high when off. (The pinouts of the 3525A/7A do not match those of the 3524 IC series.)

Operation is similar to the 3524, but with added features. The oscillator has a sync input, making it easy to lock the frequencies of several supplies, eliminating problems with beat frequencies in multiple-supply boards or systems. The shut-down circuit (also included in the 3524A) and soft-start feature simplify the design of protective circuitry, as will be seen in the next application. The totem pole (push-pull) outputs, rated at maximum 500 mA, provide fast,
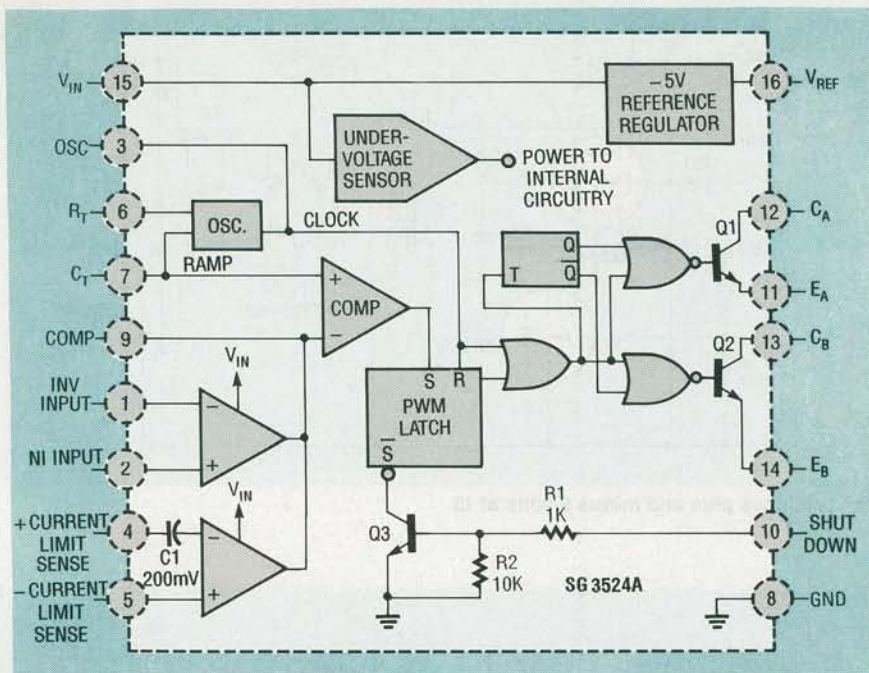
FIG. 3—THE SG3524A IMPROVES the basic device by adding undervoltage lockout, a pulse-width modulator (PWM) latch, thermal protection, and improved reference accuracy.
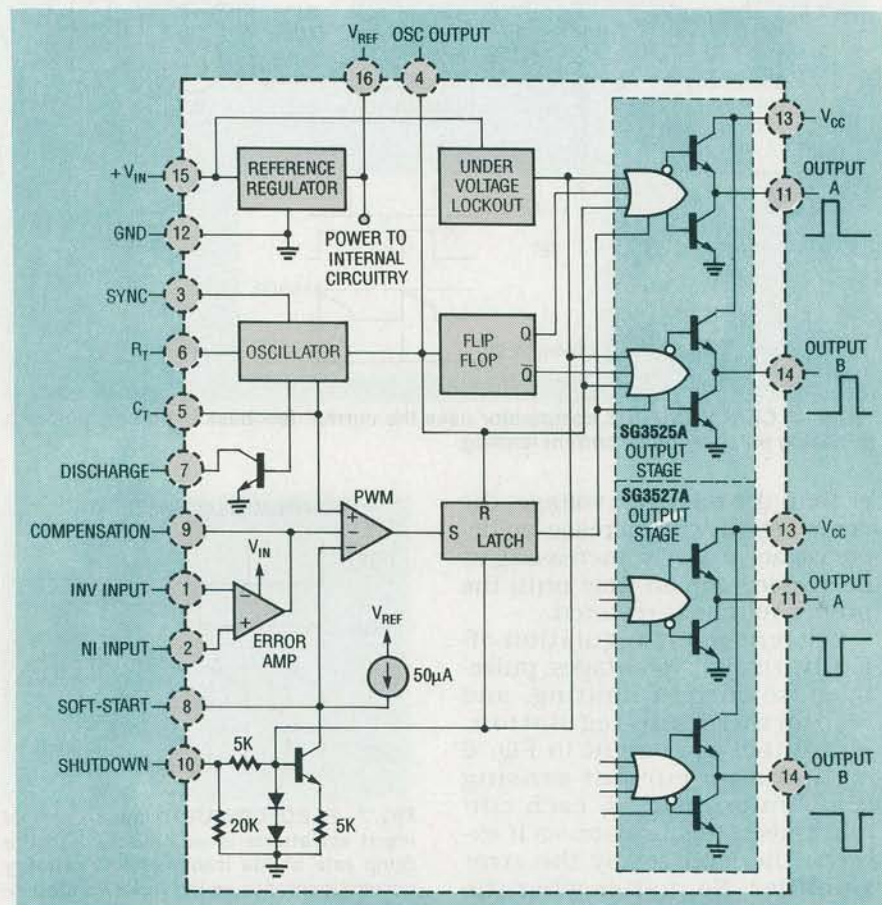

FIG. 4—THE SG3525A AND SG3527A PUSH-PULL switching regulators provide 500-mA, totem-pole outputs and oscillator synchronization.

solid switching for high and low transitions. The 3524's separate current-limit amplifier has been omitted.

Figure 5 shows a 15-watt DC-DC converter. The 200-kHz frequency (100 kHz final output) is set by R2–C2. The internal dis-

charge transistor (pin 7) allows control of the discharge time at the end of each ramp. That provides an ensured stoptime between output pulses so that, even with switching delays, both transistors cannot be on at once. A 47-nanosecond time constant is provided by R16-C2.

The 5-volt reference (pin 16) is connected to the noninverting input (pin 2) by current limiting resistor R3, while C9 provides high-frequency bypassing. Negative feedback voltage is divided by R1-R4, dividing the 6-volt output down to 5 volts. The basic theory of operation is similar to that of Fig. 2; the ramp is compared to the error signal to control the on-off switching of the outputs. On each cycle, the internal flip-flop selects either output A or B. The selected output is switched high at the start of each ramp and reset to low by the latch when the ramp voltage exceeds the error amp's output. As in Fig. 2, the direct feedback connection means there is no input to output isolation.

Compensation for closed-loop stability is provided by R6, R7 and C4. Switching spike currents are limited by R10, R11, and R12 in the output stages. Components C5 and R17 act as a "snubber," limiting switching transients from the primary.

When input power is first applied, Q1 will be off and soft-start capacitor C3 will be discharged. As C3 is charged from the internal 50-μA current source, its voltage will rise, gradually increasing the voltage to the pulse-width modulator (PWM) control's bottom input. That gradually increases the amount of time per cycle that the output is turned on, providing a "soft" rise of the output voltage, which allows the filter capacitors to charge slowly, reducing startup current surges.

If R9's current exceeds about 3 amps (0.7-volt drop), Q1 will turn on, energizing the shutdown circuit which pulls pin 8 low and discharges C3. As the current drops below 3 amps, Q1 turns off, C7 discharges, the shutdown input goes low and the soft-start capacitor provides a "soft" recovery for the power supply.

Power transformer T1 is wound on an EE25 ferrite core (0.25-inch center leg). It feeds a
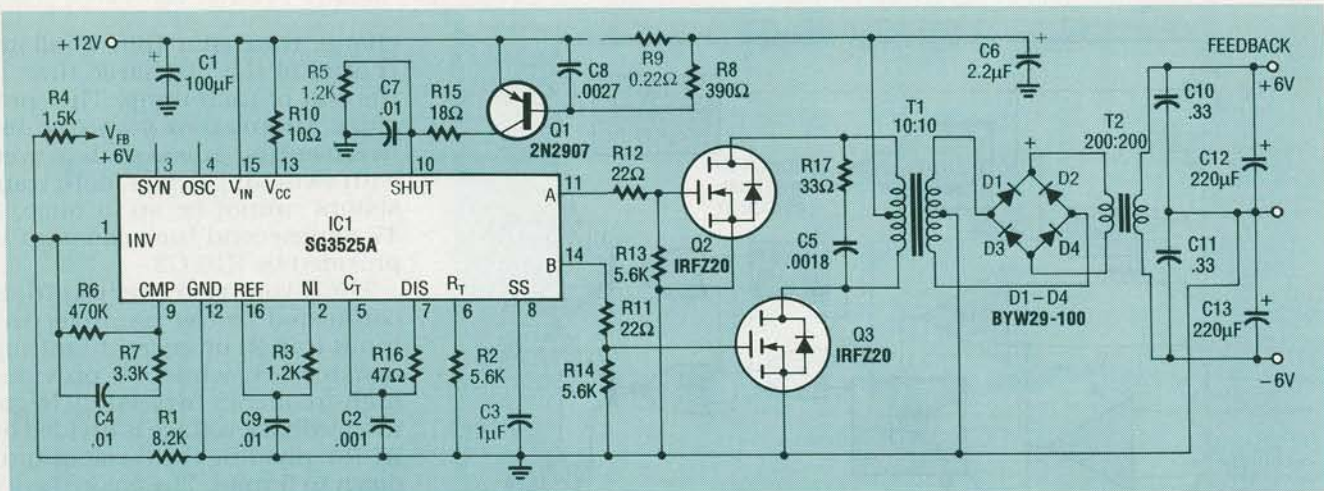
FIG. 5—A PUSH-PULL SWITCHING REGULATOR produces plus and minus 6 volts at 15 watts.

conventional full-wave bridge, providing + and − outputs. Coupled inductor T2, consisting of two coils wound on a cylindrical ferrite core, and the output capacitors filter the output to 50 millivolts peak-to-peak. Transistors Q2 and Q3 are 50-volt, 5-amp, N-channel power MOSFET's. Fast-recovery diodes must be used in the rectifier due to the high frequency; D1–D4 are 100-volt, 8-amp diodes with 35-nanosecond recovery.

Current-mode regulators

We now turn to a different class of switching regulators—current mode. Although the basic operating theory remains the same (pulse-width modulation), current-mode switching regulators differ in that the internal ramp is eliminated. In its place, the ramp-like increase in the transformer's inductive current is used for control.

Figure 6 shows the basics of a current-mode comparator. The pulse from an R-C clock sets the flip-flop, producing a high output. FET Q1 turns on and transformer current begins to flow. As the inductive current ramps upward, the feedback from current-sensing resistor R2 increases. Eventually, the feedback voltage equals the error amplifier's output, at which point the comparator resets the flip-flop, Q1 then turns off until the next clock pulse.

As with previous regulators, the feedback voltage, V_{FB}, represents the filtered output. If the feedback becomes lower or high-
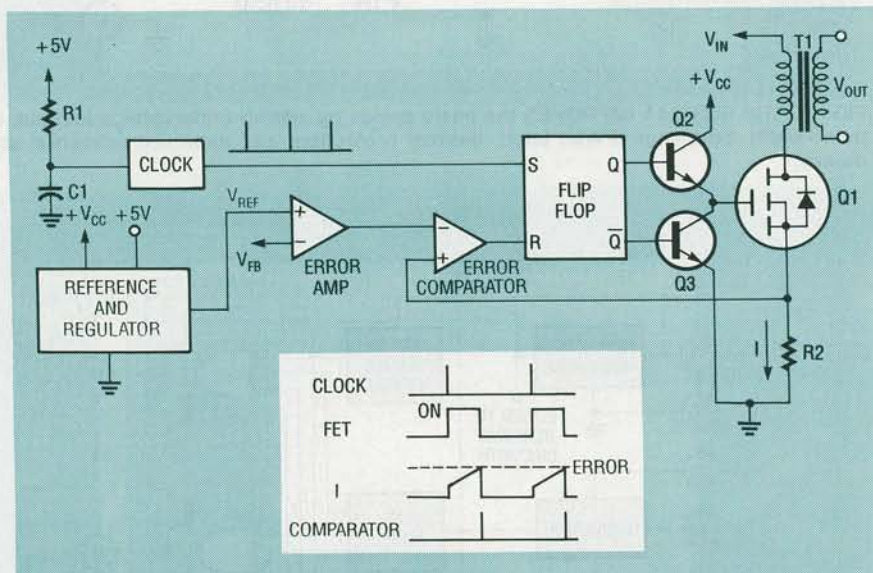

FIG.6—A CURRENT-MODE comparator uses the current feedback signal as the ramp, providing pulse-by-pulse current limiting.

er than the reference voltage, the error signal will increase or decrease accordingly, increasing or decreasing the on time until the proper voltage is restored.

Current-mode regulation offers two major advantages; pulse-by-pulse current limiting, and feedforward line regulation. Notice that the circuit in Fig. 6 contains no current-sensing comparator. Instead, each current pulse ends as soon as it exceeds the level set by the error amplifier. No matter what the cause of overload, whether transformer saturation, an output short, or input overvoltage, the circuit will limit current instantly. Pulse-by-pulse limiting also eliminates the need for a separate soft-start circuit.
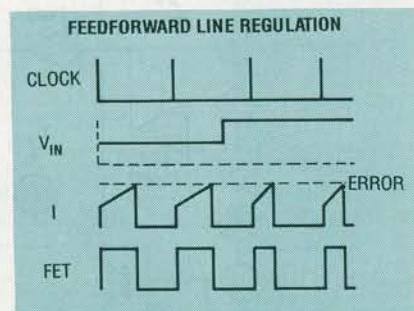

FIG. 7—FEEDFORWARD compensation of input variations is achieved when the ramp rate of the transformer's primary current increases as the input voltage increases.

Feedforward line regulation is illustrated by the waveforms shown in Fig. 7. With a fixed load, the input voltage suddenly increases. On the very next pulse,

the inductive current, I, ramps more quickly due to the increased transformer voltage. Since the feedback and the error signal have not changed, the limit is reached more quickly and the pulse width becomes shorter. Changes in line voltage are, therefore, compensated before they have a chance to affect the output.

UC3842/3/4/5

Figure 8 shows the block diagram of current-mode PWM controller IC UC3842. Compared with the circuit in Fig. 6, the UC3842 adds an undervoltage lockout and an output NOR gate. The undervoltage lockout, with hysteresis, disables the output pulses until V_{CC} rises above 16 volts. Once started, it will not drop out unless V_{CC} goes below 10 volts, a feature which prevents constant toggling between "operate" and "lockout." When disabled, the output (pin 6) goes to a high-impedance state. A "bleeder" resistor should be connected from pin 6 to ground to prevent leakage current from turning the switching FET on.

The output NOR gate implements lockout, but also serves another protective function. When the oscillator pulse is high, the NOR output will be low, the OR output high, and pin 6 low. The output cannot go high until the clock goes low. The clock is set up so that timing capacitor C1 charges through R1, and discharges through the constant current sink. By choosing a larger capacitor and smaller resistor, the charging time (clock low) can be decreased and the discharge time (clock high) increased. That allows you to establish the maximum on time, or duty cycle, which is especially important in circuits where duty cycles higher than 50% can lead to transformer core saturation.

The D2–D4-R1-R2 network between the error amplifier and the current-sensing comparator reduces the error signal so that excessive power is not lost in the current-sensing resistor. The one-volt Zener diode clamps the error signal so the maximum turn-off level will never exceed one volt.

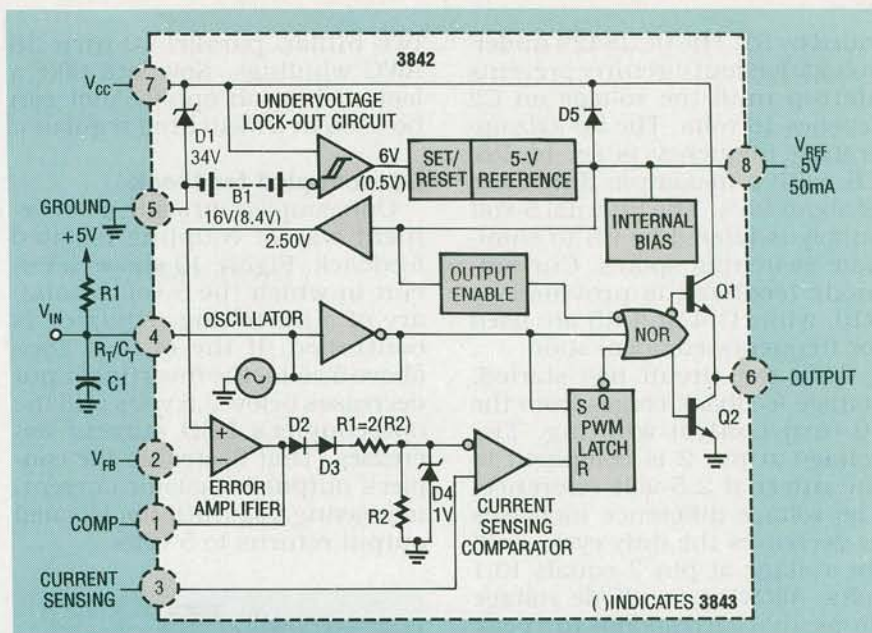UC3843 is similar to the 3842 but has a lower lockout voltage.

FIG. 8—INTERNAL BLOCK diagram of the UC3842 current-mode switching regulator IC. The UC3843 IC is similar but operates with a lower undervoltage lockout.
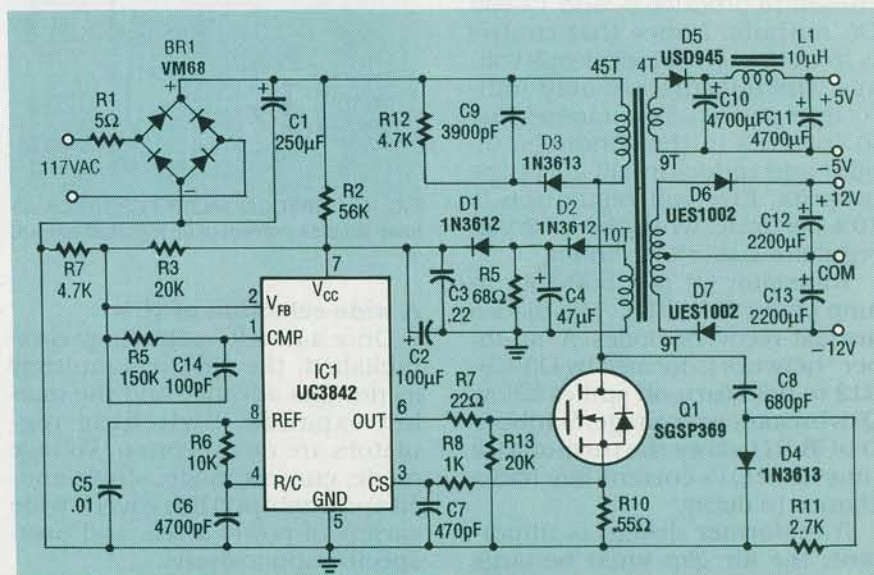

FIG. 9—THIS OFF-LINE CURRENT-MODE regulator produces isolated +5 volts and ±12 volts from 117-volt line power.

Intended for use at lower voltages, it operates at 8.4 volts, and drops out at 7.9 volts. UC3844 and UC3845 (not shown) have one added feature; a flip-flop which disables the output on alternate clock cycles. That guarantees the duty cycle will always be less than 50% for circuits where that is critical.

An off-line flyback converter

Figure 9 shows an SGS-Thomson UC3842 IC in an "off-line" flyback regulator. The circuit provides +5 volts at 4 amps and ±12 volts at 300 mA, and can deliver 27 watts.

The term "off-line" means that the regulator is on the primary side of the transformer and operates directly "off the line." The primary advantage of such a circuit is that large amounts of power can be coupled through a small, high-frequency transformer. Line operation requires high-voltage transistors and diodes, and prevents direct coupling between the output and the feedback circuit.

The line voltage is rectified and filtered by BR1 and C1. Initial startup current to the IC is pro-

vided by R1. The UC3842's under-voltage lockout circuitry prevents startup until the voltage on C2 reaches 16 volts. The 50-kHz operating frequency is set by R6-C6, with a maximum duty cycle of about 95%. The internal 5-volt supply is filtered by C5 to eliminate switching spikes. Current-mode feedback is provided by R10, while C14 and R5 are used for frequency compensation.

Once the circuit has started, voltage feedback comes from the 10-turn control winding. The voltage at pin 2 is compared to the internal 2.5-volt reference. The voltage difference increases or decreases the duty cycle until the voltage at pin 7 equals 13.1 volts. Allowing for diode voltage drops, that corresponds to a peak voltage of about 14.6 volts on the control winding. The control-to-secondary turns ratios are chosen to produce 5- and 12-volt DC outputs. Notice that control is from the control winding's voltage, the outputs are only indirectly regulated. Power losses due to currents in the windings, diodes and inductor will affect the outputs. Five-volt regulation is 10% accurate, while the ±12-volt regulator has 5% accuracy.

Transistor Q1 is a 500-volt, 5-amp power MOSFET. The diodes are fast-recovery diodes. A "snubber" network is formed by D3-C9-R12 to hold turn-off spikes below Q1's breakdown voltage. Snubber D4-C8-R11 slows the turn-off rise time until Q1's current has had a chance to decay.

Transformer design is important; the air gap must be large enough to prevent core saturation but small enough to maintain the required inductance. (Note that an air gap is not needed in balanced push-pull circuits.) In the Fig. 9 circuit, an EC35 ferrite core is used (⅜-inch dia. center leg, Ferroxcube EC35-3C8) with a 0.5 mm gap in the center leg.

The primary winding consists of 45 turns of 26 AWG wire. The 12-volt windings are each 9 turns of 30 AWG wire, wound together (bifilar). The 5-volt secondary is only 4 turns, but instead of using a heavier gauge wire, four bifilar, 4-turn windings of 26 AWG wire are used, with their ends connected in parallel. The control (feedback) winding consists of

two bifilar, parallel 10-turn 30 AWG windings. Now let's take a look at how an optoisolator can be used in a switching regulator.

Optocoupled feedback

Optocouplers provide a convenient way of coupling isolated feedback. Figure 10 shows a circuit in which the 5-volt secondary of a switching regulator is controlled. If the output goes above 5 volts, the inverting input decreases below 2.5 volts and the optocoupler's LED current decreases. That decreases the coupler's output transistor current, increasing V_{FB} until the isolated output returns to 5 volts.
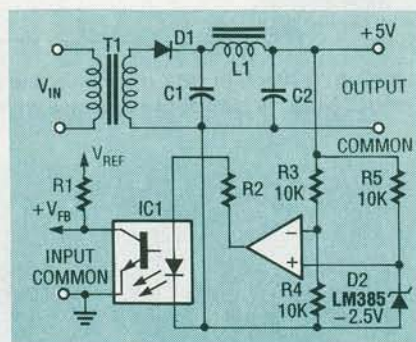

FIG. 10—OPTOCOUPLER FEEDBACK allows precise control of an isolated output.

A wide selection of IC's

Once a new IC technology is established, the offerings multiply as designs advance and the market expands. Switching regulators are no exception. Voltage mode, current mode, single-ended and push-pull IC's cover a wide variety of power levels and user-specific applications.

Table 1 summarizes some of the many IC families available. Most of the devices shown can be multiple-sourced. The part number prefixes vary from manufacturer to manufacturer, and many offer additional, proprietary devices.

It's not possible to fully describe all devices in an abbreviated table, but the listing should help direct you to data sheets for IC's to meet your needs. The 8-pin devices tend to be simpler to apply, while the 16-pin and larger IC's generally offer more complicated protective and "housekeeping" features.

The 3524/5/7 and 3842-7 families have been fully covered in this article. The 4191-3 family,

with its low operating voltage and 200-μA current drain, is ideal for battery and micropower applications. Companion micropower device 4391 provides regulated negative outputs from positive supplies. LT1070 is the only IC in the listing housed in a power IC package.

Troubleshooting hints

When troubleshooting switching regulators, always begin with the obvious. Check for input power and output shorts, broken wires, defective connectors, solder bridges, defective solder joints, bad copper traces, scorched components, and so on. It's surprising how often a good visual inspection can uncover a problem.

Make sure you have a data sheet, pinouts of the control IC, and a circuit schematic, preferably with voltages and waveforms. There is such a wide variety of IC's and operating modes that it's difficult to troubleshoot on an intuitive basis. Figure 11 shows a "generic" block diagram, which may help you to think through the circuit function-by-function.

When breadboarding temporary components, remember that switching regulators produce fast, high-current pulses. Conductor size and lead dress are important. The input filter capacitor should be close to the IC, not a foot away. If the main source of power is at a distance, add a several hundred microfarad input bypass capacitor next to the IC.

Even though you may understand the operation of switching regulators, troubleshooting them can be difficult. The IC and its circuitry perform many functions, and the failure of one can cause improper operation of the rest. For example, failure of the feedback circuit may lead to overvoltage, overcurrent, and shutdown by one of the protective features. Is the circuit dead, unstable or out of regulation? That alone may often narrow the search to one particular part of the circuit.

The following hints may help you pinpoint the problem to a specific area of the circuit. After the visual inspection, check the output for shorts or overloads and check the input source, rectifier, filter, and transformer.

TABLE 1—A SUMMARY OF SELECTED SWITCHING REGULATOR IC'S

IC Family	Manufacturers*	Mode V or I	Output (Single or Push-Pull)	Package	Supply	I_OUT Max	Reference	Comments
3524/5/7	CS, ERIC, EXAR, GE, IPS, LT, MOT, NAT, SGS, SIL, SLG, TI, UNI	V	P-P	16 Pin	8-35V	100mA	5 or 5.1V	See Article.
3842-7	CS, ERIC, IPS, LT, MOT, SGS, SIG, TI, UNI	I	S	8 Pin	8 (or 16)-25V	1A	5V	See Article.
4191-3	MAX, RAY	V	S	8 Pin	2.4-30V	150mA	1.31V	Micropower for battery applications, 200μA quiescent supply current.
4391	MAX, RAY	V	S	8 Pin	– 4 to – 30V	100mA	1.25V	Inverting, micropower for battery applications, 250μA supply at 4V.
5560 5562	CS, IPS, SIG	V	S	16 Pin 20 Pin	10.5-18V 10-16V	40mA 100mA	3.72V 3.80V	Full-featured, flexible.
5561		V	S	8 Pin	10.5V-18V	20mA	3.75V	Lower cost, fewer housekeeping functions.
493/4/5 593/4/5	CS, EXAR, GS, IPS, MOT, NAT, TI, UNI	V	P-P	16 or 18 Pin	7-40V	200mA	5V	
μA78S40	MOT, NAT	V	S	16 Pin	2.5-40V	1.5V	1.24V	Universal subsystem IC.
125/7	IPS, SIL	V	P-P	16 Pin	8-35V	100mA	5.1V	
33060/ 34060/ 35060	IPS, MOT	V	S	14 Pin	7-40V	500mA	5V	
1060	IPS, PLES	V	S	16 Pin	20mA into 5V shunt regulator	40mA	3.7V	
LT1070	LT	I	S	5 Pin Power	3-40V	5A	1.24V	Self-contained power IC.

*Manufacturers: CS = Cherry Semiconductor, ERIC = Ericsson, EXAR = Exar, GE = GE/RCA/Harris, GS = Gold Star, IPS = Integrated Power Semiconductor, LT = Linear Technology, MAX = Maxim, MOT = Motorola, NAT = National Semiconductor, RAY = Raytheon, SGS = SGS-Thomson, SIG = Signetics, SIL = Siliconix, SLG = Silicon General, TI = Texas Instruments, UNI = Unitrode
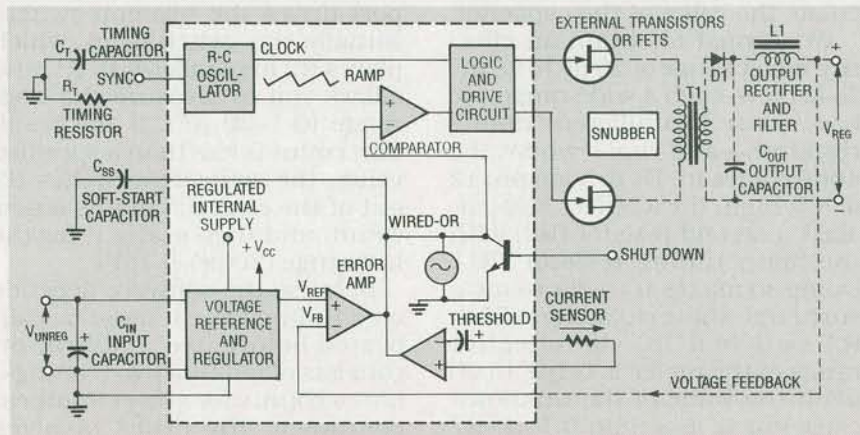

FIG. 11—THIS "GENERIC" BLOCK DIAGRAM of a switching regulator is useful in sorting out the functions which make up the circuit.

Sometimes a failure which looks like it might have been caused by output overload is actually caused by a low input voltage. When the input voltage drops, the regulator's duty cycle increases, raising the input current. The increased current may further drag down the voltage, resulting in even higher current drain, until an input fuse or circuit breaker trips or something burns out.

If the output is dead, check the rectifier and filter, the drive transistors and the output transformer or inductor. Before replacing damaged components check any snubber or surge-suppres-

sion components. Failure of those will allow high voltage spikes, possibly destroying switching transistors or rectifier diodes. Incidentally, always use identical or approved replacement parts for diodes and switching transistors. Slow "garden variety" components will fail quickly, possibly taking other components with them.

Before replacing the IC, go through the circuit function-by-function. Try to narrow the problem to one area of the circuit and see if any external components have failed. Is the IC's internal regulated voltage correct? If not, the failure almost certainly is in the IC. Is the oscillator running? If not, check the resistor and capacitor before replacing the IC. Check the soft-start capacitor and the external shutdown input, if your circuit has them. Check any compensation components, especially if the output is oscillating or unstable.

If all of the above are working but the output is incorrect, the problem is most likely either the IC or the voltage feedback circuitry. A malfunctioning feedback circuit is always tricky to troubleshoot, especially in a device as complex as a switching regulator.

The best advice is to start at the output and go step-by-step through the feedback circuit. The voltage divider's input-to-output ratio should be correct, even if the voltage isn't. An op-amp or comparator's output should be high if the positive input is higher than the negative input; otherwise, it should be low. (Note, though, that the IC connects two amplifiers and other circuitry together in a wired-OR connection. Any one of several problems can bring the error amp's output low.) Check any feedback windings and rectifiers, optocouplers, and so on. If you still haven't found the problem, replace the IC.

Troubleshooting switching regulators can be tricky. Just remember to go through the circuit step-by step, and keep the basics in mind when you encounter problems. **R-E**